CHAMBERS'S EDUCATIONAL COURSE

ELECTRICITY

BY

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OF THE EDINBURGH INSTITUTION

New Edition

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PREFACE

TO THE NEW EDITION.

THE well-merited success and popularity of Dr Ferguson's work on Electricity has led the publishers to issue a new edition adapted, by alterations and extensive additions, to the present state of scientific investigation, and current methods of studying the subject. The book aims at giving a popular and accurate account of the chief experimental facts of the science of Electricity and Magnetism, and of the exact laws which have been deduced from them. It is designed to meet the requirements of students at science classes, science colleges, and technical institutes, as well as Teachers and private pupils; and as an introduction to electrical science as a whole, should be valuable to those engaged in telegraphy, telephony, electro-metallurgy, and the other practical applications of Electricity.

The work has been revised and largely re-written for the present edition; and a considerable amount of new matter added. This was rendered necessary, both from the recent increase of our knowledge of the subject, and also from the fact that certain modern ideas and methods of explanation—such as Potential—required to be introduced. In the experimental part of the subject, constant reference has, of course, been made to Faraday's researches, and to such works as those of Wiedemann and Mascart. In the theoretical explanation, equally constant reference has been made to

the writings of Sir William Thomson and Professor J. Clerk-Maxwell. The adopted systems of practical and absolute units have been given, and the most approved methods of measuring electrical and magnetic quantities explained.

An attempt has been made to give the leading mathematical formulæ connected with the subject, as far as that is possible with the aid of only elementary mathematics. Care has been taken to include important recent inventions, and special chapters on the Practical Applications of the subject have been given. In this way it is hoped that the work will be found of service not only to those students who wish to obtain an experimental and elementary theoretical knowledge of the subject; but also to those who are engaged in practical work, and who aim at being practical electricians.

2*d October* 1882.

CONTENTS.

CENTIMETRE-GRAMME-SECOND (C. G. S.) SYSTEM OF UNITS.

FUNDAMENTAL UNITS:

Unit of Length .... One Centimetre.
Unit of Mass .... One Gramme.
Unit of Time .... One Second.

The Centimetre		=	0·3937 inch.
The Metre .... =	100 Centimetres ...	=	39·37 inches.
The Millimetre .. =	$\frac{1}{10}$ Centimetre	=	0·03937 inch.
The Gramme		=	15·432 grains Troy.
The Kilogramme =	1000 Grammes	=	2·2 pounds Avoird.
The Milligramme =	$\frac{1}{1000}$ Gramme.		

DERIVED UNITS:

Velocity.—The unit of velocity is the velocity of one centimetre per second.

Acceleration.—The unit of acceleration is the acceleration of one centimetre-per-second per second.

Gravity.—g. = 981·1.

Force.—The one of force—*One Dyne*—is that which, acting on one gramme for one second, gives it a velocity of one centimetre per second.

Work.—The unit of work—*One Erg*—is the work done in overcoming one dyne through one centimetre.

Heat.—The unit of heat—*One Caloric*—is the heat required to raise the temperature of one gramme of water from 0° to 1° C. Dynamical equivalent of one Caloric, that is, Joule's Equivalent = 42,000,000 Ergs. Hence J = 42,000,000 (C. G. S.).

Since paragraph 187 was printed, a slight change in the names of the Practical Electrical Units has been agreed upon by the International Congress of Electricians at Paris.

Instead of the *Weber*, the name *Coulomb* is adopted, so that the Coulomb = the unit of quantity = $\frac{1}{10}$ C. G. S.

The name *Ampère* is given to the practical unit of current, so that the Ampère = the unit of current = $\frac{1}{10}$ C. G. S.

ELECTRICITY.

Part I.—MAGNETISM.

CHAPTER I.

1. MAGNETISM is the influence in virtue of which certain bodies called magnets have the peculiar property, among others, of attracting iron. No substance is totally unaffected by a magnet; in iron the effects are most marked. Magnets are either *natural* or *artificial.* Natural magnets consist of the ore of iron called magnetic, familiarly known as loadstone, the chemical composition of which is given by the formula Fe_3O_4. This ore, although capable of becoming magnetic, only occasionally occurs naturally magnetised. The loadstone appears to have been first discovered in Magnesia, in Asia Minor, hence the name *magnet.* Artificial magnets are, for the most part, straight or bent bars of tempered steel, which have been magnetised by the action of other magnets, or by the galvanic current.

2. The power of the magnet to attract iron is by no means equal throughout its length. If a small iron ball, suspended by a thread, be placed in succession opposite different parts of a bar magnet (fig. 1), it is powerfully attracted at the ends, but not at all in the middle, the magnetic force increasing with the distance from the middle of the bar. The ends of the magnet where the attractive power is greatest are called its *poles.* The greater strength of the magnetic power at the poles of a magnet may also be shewn by dipping it in iron filings, when a tuft of filings adheres to each extremity, and the middle is left bare. By causing a

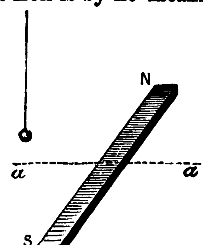


Fig. 1.

magnetic needle moving horizontally to vibrate in front of the different parts of a magnet placed vertically, and counting the number of vibrations, the rate of increase of the magnetic force with the distance from the centre may be found exactly, as will be afterwards shewn.

Fig. 2 gives a graphic view of this increase. NS is the magnet; thè lines *n*N, *aa*, &c. represent the strengths at the points N, *a*, &c. of the magnet; and the curve of

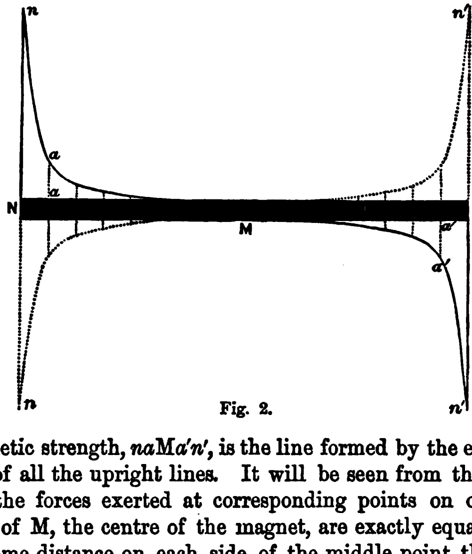


Fig. 2.

magnetic strength, *na*M*a'n'*, is the line formed by the extremities of all the upright lines. It will be seen from the figure that the forces exerted at corresponding points on opposite sides of M, the centre of the magnet, are exactly equal; that for some distance on each side of the middle point the force is nothing, and that it increases with great rapidity towards the ends. The centres of gravity of the areas M*n*N*n* and M*n'*S*n'* may be shewn to be the poles of the magnet, which must therefore be situated near, but not at its extremities. The *Magnetic Axis* of a magnet is the line joining the poles.

3. If fine iron filings be strewn on a sheet of stiff drawing-paper under which there is a strongly magnetised bar, and the paper be gently tapped, the particles will arrange themselves in curved lines, crowded together at the poles, and

farther apart as we recede from them (fig. 3, *a*). The lines are called *lines of magnetic force.* The space through which a magnet exercises a finite force has been named by Faraday its *Magnetic Field.* The effect apparently produced by the magnet ought to be referred to the mediate action of the magnetic field, rather than to the direct action of the magnet, since, as will be shewn later, the same effects may be produced without the presence of a magnet. In other words, the presence of a magnet produces a condition of stress in the medium or ether in its neighbourhood. This condition of stress manifests itself in various ways (such as by the deflection of small magnets, &c.), which are usually explained as being caused by the magnet. But as the same condition of stress and the consequent effects can also be produced by a current of electricity, it is considered better to attribute the apparent action of the magnet to the action of the magnetic

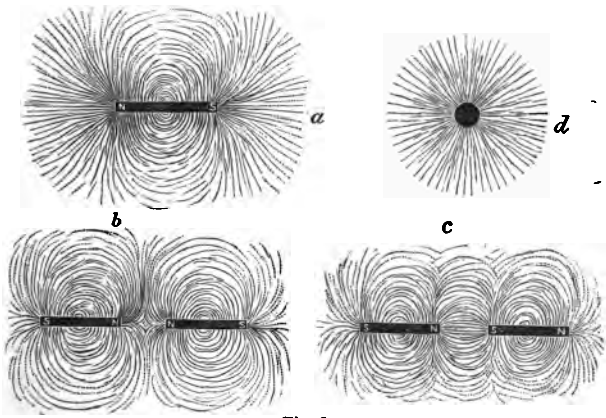


Fig. 3.

field. *A line of magnetic force* is such that its direction at any point is that of the resultant force exerted there, and the magnetic field may be so mapped out that the number of lines in unit of area at any place gives a measure of the intensity of the magnetic force there. If we place, at any point in the field, a small needle, free to turn about an axis,

it will always take up a position tangential to the line of force passing through its centre. And if it were moved always in the direction in which it is pointing, its centre would trace out a line of force. Fig. 3, *a*, shews the lines of force in the neighbourhood of a single bar magnet; *b*, of two magnets with like poles adjacent; *c*, of two magnets with unlike poles adjacent; *d*, of a single pole.

A *uniform magnetic field* is one in which the lines of force are parallel to and equidistant from each other, such as any small space in the field at some distance from the poles. Any station on the earth's surface unaffected by the presence of magnetic matter in the neighbourhood is also a uniform field—the direction of the force being that of the dipping needle there (sect. 35).

4. If between the magnet and the ball in fig. 1 a sheet of pasteboard, or any other material not containing iron, be interposed, the action would not be lessened. It is the peculiarity of magnetic action that it is transmitted through all substances not decidedly magnetic with equal facility. Most substances are thus, so to speak, magnetically transparent.

5. A magnet has, then, two poles or centres of magnetic force, equal in strength but of opposite properties. To shew this, let a magnet, NS (fig. 4), be suspended by a stirrup of paper, M, hanging from a cocoon thread (or any fine thread without torsion). When the magnet is left to itself, it takes up a fixed position, one end pointing northwards, and the other south. The north pole cannot be

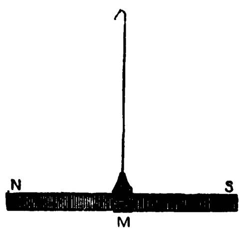


Fig. 4.

made to stand as a south pole, and *vice versâ;* for though disturbed, the magnet, as soon as it is released, returns to its original position. Here, then, is a striking dissimilarity in the poles, by means of which we are enabled to distinguish them as *north pole* and *south pole.* If we now try the effect of another magnet upon the suspended one, we shall find that the north pole of the suspended magnet is attracted by one of the poles of the second magnet and is repelled by the

other, and similarly with the south pole; where the one pole attracts, the other repels. If, now, the second magnet be hung like the first, it will be found that the pole which attracted the north pole of the first magnet is a south pole, and that the pole which repelled it is a north pole. Poles of the same name are called *like* poles; of opposite names, *unlike* poles. We thus learn, that *each magnet has two poles, the one a north, and the other a south pole, alike in their power of attracting soft iron, but differing in their action on the poles of another magnet, like poles repelling, and unlike poles attracting, each other.* On this account a magnet is said to be Polarised.

6. When a small magnetic bar, or needle, as it is called (fig. 5), is delicately balanced by means of a small inverted agate cup on a fine hard point, it may be used as a magnetoscope to indicate whether a piece of iron or steel is magnetised or not. If the poles of the needle are attracted equally by either end of the iron or steel it is not magnetised; but if one pole is attracted and the other repelled, the piece of iron or steel under examination is magnetised.

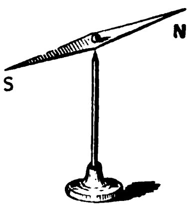


Fig. 5.

7. The fact of the freely suspended magnet taking up a fixed position, has led to the theory, that the earth itself acts much in the same way as a huge magnet, with its north and south magnetic poles in the neighbourhood of the poles of the axis of rotation, and that the magnetic needle or suspended magnet turns to them as it does to those of a neighbouring magnet. All the manifestations of terrestrial magnetism give decided confirmation of this theory. It is on this view that the French call the north pole of the magnet the south pole (*pôle austral*), and the south the north pole (*pôle boréal*); for if the earth be taken as the standard, its north magnetic pole must attract the south pole of other magnets, and *vice versâ.* In England and Germany, the north pole of a magnet is the one which, when freely suspended, points to the north, and no reference is made to its relation to the magnetism of the earth. Clerk Maxwell

and others use the term Boreal to indicate the magnetism near the north pole of the earth and the south end of a magnet, and Austral that of the south pole and north end.

8. It might be thought that, by dividing a magnet at its centre, the two poles could be insulated, the one half containing all the north polar magnetism, and the other the south. When this is done, however, each half becomes a complete magnet—the broken end of each having a new pole opposite to and weaker than the original pole of the piece. This and other facts mentioned in sect. 27 prove that *we can never have one kind of magnetism unless associated with the same amount of the opposite magnetism.*

9. *Nature of Magnetism.*—To explain the phenomena of magnetism several theories have been propounded. One of these attributes the power of a magnet to the presence in it of two fluids called respectively the northern and the southern fluid. The molecules of either of these two fluids attract those of the other kind, but repel their own. The fluids are confined to the molecules of the magnetic substance, and are always in equal quantities—that is, every substance has always equal north and south magnetism. In a non-magnetised piece of iron the fluids in each molecule are supposed to be thoroughly mixed. To magnetise it the fluids in every molecule must be separated and concentrated at its two ends—the more complete the separation, the stronger is the magnetisation. In such a substance as soft iron the separation is effected only during the presence of the magnetising agent. In steel again the separation is effected with difficulty, but continues in consequence of the coercive force (sect. 11).

A more recent theory suggests, that all substances capable of becoming magnetic consist of particles, each of which is a permanent magnet; that these infinitesimal magnets have their poles turned in all the different directions, so as to neutralise each other when the whole is not magnetic; that magnetisation has the effect of bringing the poles of these particles round so as to lie in the same direction; that this coincidence of poles in the case of soft iron takes place only when the iron is under the influence of a magnet or of an electric

current; that in the case of steel it takes place permanently; and that the intensity of magnetisation depends upon the completeness of the coincidence. This way of conceiving of the composition of a magnet is both simple and satisfactory, and agrees with the fact that there is a limit to the magnetisation of a magnet. Ampère's theory of the electric constitution of a magnet, which will be afterwards described, introduces an entirely different view of it.

It may be noticed here that the magnetism of which a substance is capable depends in some way on the closeness of its particles. For the most magnetic substances, as iron and nickel, have apparently their particles most densely packed, as is seen by the ratio of their specific densities to their atomic weights. Again, wherever a body is compressed in one direction more than in any other, it shews magnetic properties strongest in that direction, notably in crystals. The change produced by rise of temperature goes to strengthen this view (sect. 26).

10. *Magnetic Induction.*—When a short bar of soft iron, *ns* (fig. 6), is suspended from one end, S, of the magnet, NS,

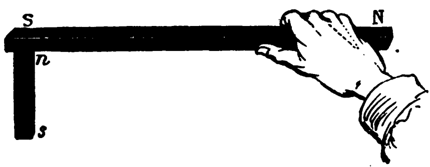


Fig. 6.

it becomes for the time powerfully magnetised. It is found to possess a north and a south pole, like a regular magnet, as may be seen by testing with the small magnetic needle (fig. 5); and if its lower end, *s*, be dipped into iron filings, it attracts them as a magnet would do. When it is taken away from NS, the great mass of the filings fall off, and nearly all trace of magnetism disappears. Actual contact between the magnet and the bar is not necessary to produce these effects. Any piece of soft iron placed in a magnetic field exhibits magnetic properties, which it loses to a greater or less extent when

removed. For example, an ordinary soft-iron poker held in the direction of the earth's magnetic force is found to possess, in the Northern Hemisphere, a north pole at its lower end and a south pole at the upper: this is proved by the upper end always attracting the marked or north pole of a needle and repelling the south pole. If the poker be inverted, we find that the end which before was a south pole, is now a north pole. This shews that the magnetisation produced is not permanent. In such cases the bar and poker are said to be magnetised by *induction*, and the action is called *magnetic induction.* If the inducing magnet be strong enough, the induced magnet, *ns*, when in contact, can induce a bar like itself, placed at its extremity, to become a magnet; and this second induced magnet may induce magnetism in a third; and so on, the action being, however, weaker with every additional magnet. As was pointed out in sect. 3, the explanation of this and similar phenomena should be referred to the action of the magnetic field.

11. *Coercive Force.*—If a steel bar be used for this experiment, a singular difference is observed in its action; it is only after some time that it begins to exhibit magnetic properties, and then they are feebler than in the soft-iron bar. When the steel bar is removed, it does not part instantly with its magnetism, as the soft-iron bar, but retains it permanently. Steel therefore, in the first instance, resists the assumption of magnetism; and, when assumed, resists its withdrawal. This is said to be due to a *coercive force.* The harder the temper of the steel, the more is the coercive force developed in it. This resistance offered to magnetisation and demagnetisation differs very much in different substances, and in any one substance is greatly affected by such processes as hammering, &c., and in the case of iron and steel by the temper. For example, steel when soft is almost as easily magnetised as soft iron; but hard steel, in virtue of its great coercive force, is the best substance to make permanent magnets of. If, when the poker is held in the position above described, a few sharp blows are given to it with a hammer, it retains some of its magnetic power, and the poles are no longer reversed when the poker is inverted. It is in this way

probably that tools become magnetised. On the other hand a steel magnet loses some of its magnetism when hammered, and it is probably for this reason that a magnet is weakened by a fall. Whenever large masses of iron are stationary for any length of time, they are sure to give evidence of magnetisation, and it is to the inductive action of the earth acting for ages that the magnetism of the loadstone is attributed. It is this force also, in the loadstone, which enables it to retain its magnetism. The polarised condition of iron under induction seems to indicate that a substance which is attracted by a magnet must itself become magnetic. The attraction between a magnet and soft iron is thus essentially the same as that between two magnets. Hence we may conclude that *magnetic attraction and repulsion take place only between bodies which are magnetised either permanently or temporarily.*

12. The magnetisation induced by a given magnetising force depends upon the substance acted on. Iron is capable of by far the most intense magnetisation, and next to it come nickel and cobalt. In these the magnetisation is in the direction of the magnetising force; such substances are called Paramagnetic, Ferromagnetic, or Magnetic. In bismuth the induced magnetism bears a very small ratio to the magnetising force, and is in the direction opposite to the magnetising force. It and similarly affected substances are called Diamagnetic. All substances, when subjected to a sufficiently powerful magnetising force, are found to be either Paramagnetic or Diamagnetic.

13. Faraday was the first (1845) to shew that all bodies are more or less affected by magnetic influence, and his beautiful researches on the subject have opened up a new field in the domain of science. He found that the magnetism of bodies was manifested in two ways—either in being attracted by the magnet, as iron; or in being repelled, like bismuth.

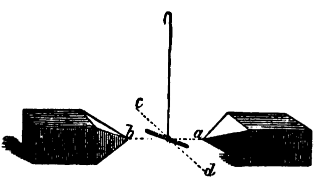


Fig. 7.

When a needle or slender rod of iron is suspended between the poles of a magnet, as in fig. 7, being attracted by them, it takes up a position of rest on the line *ab*, joining the two poles. When a substance behaves itself in this manner, it is said by Faraday to be *paramagnetic*, and to place itself *axially*, *ab* being the axis. A rod of bismuth, on the other hand, being repelled by the poles of the magnet, comes to rest in the line *cd*, at right angles to *ab*. Bismuth and the like substances, he calls *diamagnetic*, and they are said to place themselves *equatorially*, *cd* being the equator. These terms, being both definite and graphic, have been universally adopted. Magnetic is the term used by Faraday to indicate magnetism of either sort, although in general language it is understood to refer to paramagnetic bodies, such as iron, &c. Paramagnetic bodies, then, are those which manifest the same properties with regard to the magnet that iron does; and diamagnetic bodies are those which, like bismuth, shew opposite but corresponding properties; so that in circumstances where paramagnetic bodies place themselves axially, diamagnetic bodies place themselves equatorially; and where the former are attracted, the latter are repelled, and *vice versâ*. A paramagnetic substance, not in the elongated form, but in a compact shape, such as that of a ball or a cube, is attracted by either pole of the magnet, when suspended near it; a ball or cube of a diamagnetic, on the other hand, experiences, when so placed, repulsion. They may also be distinguished by the fact that paramagnetic bodies tend to place themselves where there are most lines of force in unit space, and diamagnetic bodies where there are fewest lines of force.

14. The paramagnetism of iron, nickel, and cobalt becomes manifest in the presence of magnets of ordinary power; but the magnetism of most other substances is so feeble as to be developed only under the influence of the strongest magnets. Electro-magnets are selected for investigations on the magnetism of bodies, as they can be made of a strength far outrivalling that of permanent magnets. Fig. 8 represents an electro-magnet which may be employed for this purpose. The soft-iron horse-shoe, PPP, enveloped towards its extremities in the coils of insulated copper wire *cc*,

which communicate with a galvanic battery by the wires *w*, is fixed in an upright wooden frame. The ends or poles of the magnet rise slightly above the table or board which forms the upper part of the frame. In order conveniently to suspend substances between the poles, and to protect them while under observation from currents of air, a glass frame of simple construction (fig. 9) is made to fit the table. The upper plate of the frame admits a wooden ring, into which an upright glass tube is fitted. The thread by which the needle is suspended is wound round a slender movable bobbin at the top, so that it can be elevated or lowered to the proper position. To modify and direct the action of the magnet, two pieces of soft iron (fig. 7) are made to rest on the end faces; these are pointed at one extremity, and flat at the other, so that the force of the magnet may be concentrated in the points when they are turned towards each other, or diffused over the opposite flat surfaces when their position is reversed.

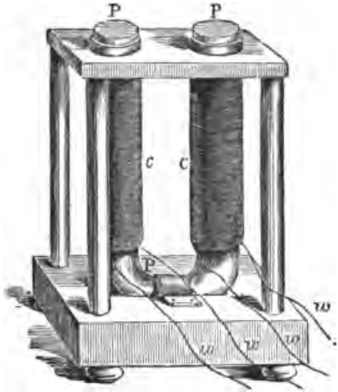


Fig. 8.

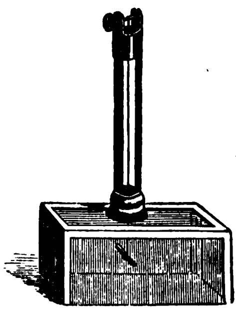


Fig. 9.

15. To observe the effect of the magnet on liquids, Faraday placed them in long tubes of very thin glass, and suspended them as in the case of solid needles. It was found that some arranged themselves axially, and others equatorially. The attraction and repulsion that liquids experience in the

presence of the magnet has been well shewn by Plücker. A large drop of liquid is placed in a watch-glass (figs. 10, 11), and laid upon two poles of the shape shewn in the figures. If the liquid be paramagnetic, the surface becomes depressed at the interval between the poles, and heaped up over the

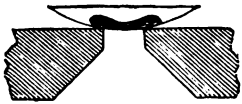


Fig. 10.

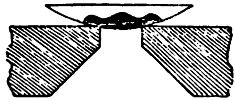


Fig. 11.

extreme edges of them (fig. 10). A diamagnetic liquid, on the other hand, shews a depression at each edge of the poles, and a heaping up at the centre (fig. 11).

16. The magnetic nature of flames and gases has also been studied. When the flame of a candle is brought between the poles of a magnet, it is repelled by them, and thrown out horizontally into an equatorial position. To ascertain the magnetism of gases, Faraday inflated soap-bubbles with them, and their para- or dia- magnetism was exhibited by their being attracted or repelled by the poles. He ascertained the same by causing the gases to flow out from glass tubes in the presence of the poles, when the magnetic character of the gas was shewn by its choosing an axial or equatorial means of egress.

17. The following lists include the more common substances in the order of the intensity of magnetisation of which they are capable:

Paramagnetic.—Iron, nickel, cobalt, manganese, chromium, titanium, palladium, paper, sealing-wax, peroxide of lead, plumbago, red-lead, sulphate of zinc, shell-lac, vermilion, charcoal, proto- and per- salts of iron, salts of manganese, oxygen, air.

Diamagnetic.—Bismuth, antimony, zinc, tin, cadmium, sodium, mercury, lead, silver, copper, gold, arsenic, uranium, tungsten, rock-crystal, mineral acids, alum, glass, litharge, nitre, phosphorus, sulphur, resin, water, alcohol, ether, sugar, starch, wood, bread, leather, caoutchouc, hydrogen, carbonic acid, coal-gas, nitrogen.

18. The nature of the medium in which the body under examination moves, exerts a powerful influence on the nature and amount of the magnetism it exhibits; thus, if a glass tube be filled with a solution of the proto-sulphate of iron, and suspended in air between the poles, it will place itself axially. It will do the same if made to move in water, or in a more dilute solution of the proto-sulphate of iron. It will be indifferent in a solution of the same strength, but it will place itself equatorially in a stronger solution. In short, the same substance may appear paramagnetic, indifferent, or diamagnetic, according to the nature of the medium in which it moves. As a general rule, a body shews itself paramagnetic towards one less paramagnetic than itself, indifferent towards one equally magnetic, and diamagnetic towards one more paramagnetic than itself. The same takes place, *mutatis mutandis*, with diamagnetic substances. This has given rise to the theory, that there is no such thing as diamagnetism *per se*, and that bodies are diamagnetic only in media of greater paramagnetic power than their own. This view of the case is, however, rendered highly improbable by some of Verdet's experiments in connection with magnetic action on polarised light, which prove that magnetic and diamagnetic bodies do possess opposite properties.

19. *Form of Magnets.*—Artificial magnets are generally either bar magnets or horse-shoe magnets. Powerful magnets are often made of several thin bars of steel placed side by side with their poles lying the same way, and bound together by a brass screw or frame. Three or four bars

Fig. 12.

may be put up into a bundle, and these again into bundles of three and four (fig. 12). Such a collection of magnets is called a *magnetic magazine or battery*. A magnet of this kind is more powerful than a solid one of the same mass and size, because thin bars can be more strongly and

regularly magnetised than thick ones. But the joint strength of the compound magnet is much less than the sum of the strengths of its components, for the reason mentioned in sect. 25. Fig. 13 represents a horse-shoe magnetic magazine. The central lamina protrudes slightly beyond the others, and to it the armature (sect. 20) is attached, and by this means the sustaining power of the magnet is much increased. The horse-shoe magnet is the most suitable for lifting; the bar magnet, for other purposes, such as counteracting the directive action of the earth's magnetism. A natural magnet is shewn in

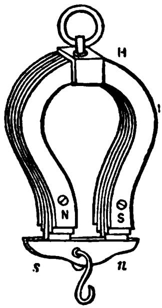


Fig. 13.

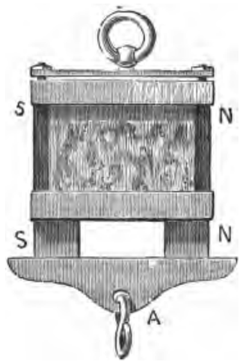


Fig. 14.

fig. 14. It is a rectangular block of magnetic iron ore, with pieces of soft iron, NN and SS, bound to its poles by a brass frame encircling the whole. These pieces of iron apparently concentrate and so very much increase the effective power of the magnet. The lower ends of the soft-iron bars act as the poles, and support the armature, A.

20. *Magnetic Armatures or Keepers* are pieces of soft iron that are placed at the extremities of magnets to preserve their magnetic power. When magnets are allowed to remain any length of time without such appendages, they lose considerably in strength in consequence of the disturbing influence of terrestrial magnetism; but when they are provided with them, their magnetism is kept in

a state of constant activity. The reason of this is to be attributed to magnetic induction. The horse-shoe magnet, NHS (fig. 13), magnetises by induction the armature *sn*, so as to have the south pole *s* next to N, and the north pole *n* at the opposite extremity. The pole S, by virtue of its magnetic affinity, powerfully attracts the north pole *n*, thus formed, and adds its own inducing influence to heighten the magnetic condition previously induced in the armature by the pole N. The armature, from the combined action of both poles of the horse-shoe magnet, is thus temporarily converted into a powerful magnet, with its poles lying in an opposite direction to that of the primary poles. The original magnet is, in consequence, brought into contact with one of its own making, which shields it from terrestrial disturbance. At the same time the keeper diminishes greatly the influence of the magnet upon surrounding objects. The attachment of the armature to the magnet is greater when its contact with the magnet is made by a rounded edge instead of a plane surface. It is due to the mutual attractions of the magnet and armature that a much greater weight can be sustained by the armature thus placed, than what the single poles can together sustain. Two bar magnets may be armed in the same way by laying them at some distance apart parallel to each other, with their unlike poles towards the same parts, and then connecting their extremities by two pieces of soft iron (fig. 17). When a magnet, such as a compass-needle, is free to take up the position required by the magnetism of the earth, the earth itself plays the part of an armature.

21. *Magnetisation—By Magnets.*—In sects. 10 and 11, certain circumstances were mentioned in which pieces of iron and steel become magnetised. Several other processes have been invented by which iron and steel bars can be permanently magnetised. They may be classed under two heads, according as other magnets or the galvanic current is employed. In *single touch*, the bar to be magnetised, which for shortness we shall call A, is stroked ten to twenty times in the same direction, along its entire length and on both sides, with one pole of the magnetising bar. The magnetising bar will be called B. Or this may be done to

one half of A with one pole of B, and then to the other half with the other pole—each stroke beginning at the centre of A. In every case B must be carried back to the beginning of a new stroke, in an arch. The new magnet has, at the end where B is raised, a pole opposite to the magnetising pole of B. In *divided touch* (fig. 15), the latter

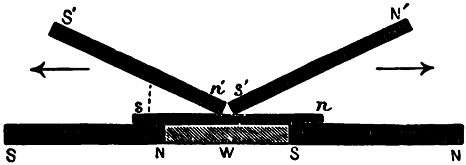


Fig. 15.

process is carried on simultaneously with two magnets, Bs, equally inclined to A, at about 30°, and prevented from touching. In *double touch,* two Bs inclined to A at about 15°, and

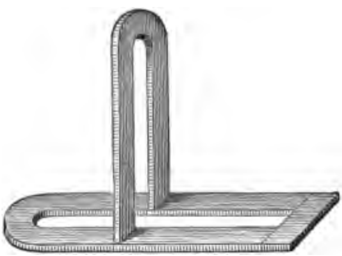


Fig. 16.

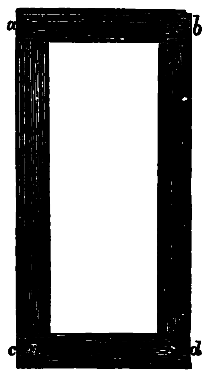


Fig. 17.

prevented from touching by a piece of wood, are drawn together backwards and forwards along the whole length of A, beginning and ending the operation at the centre of A. Divided touch gives the best results.

For horse-shoe magnets, Hoffer's method is generally followed. The inducing magnet (fig. 16) is placed vertically on the magnet to be formed, and moved from the ends to the bend, or in the opposite way, and brought round again, in an arch, to the starting-point. A soft-iron armature is placed at the poles of the induced magnet. That the operation may succeed well, it is necessary for both magnets to be of the same width.

By the Galvanic Current.—The bar to be magnetised is placed with soft-iron armatures on its extremities, in the interior of a short thick coil of insulated wire, connected with a galvanic battery. The circuit should be completed when the coil surrounds the centre of the bar, which is then moved backwards and forwards always to the ends as in double touch. The process is finished by breaking the circuit when the centre of the bar is again at the coil. The magnetism induced in this way is much weaker than that got when the same strength of current is employed through the intervention of an electro-magnet. Thick bars or horse-shoes of the hardest temper can be easily magnetised with a strong electro-magnet by rubbing each half of the bar or horse-shoe on a different pole, beginning at the middle, after the method of single touch. See ELECTRO-MAGNETISM. Electro-magnets far transcend permanent magnets in power.

22. *Saturation Point.*—Magnets, when freshly magnetised, have sometimes more magnetism than they can retain permanently. In that case, they gradually fall off in strength, till they reach a point at which their strength remains constant. This is called the *point of saturation.* We may ascertain whether a magnet is at saturation by magnetising it with a more powerful magnet, and seeing whether it retains more magnetism than before. The saturation point depends on the coercive force of the magnet, and not on the power of the magnet with which it is rubbed. When a magnet is above saturation, it is soon reduced to it by repeatedly drawing away the armature from it. After reaching this point, magnets will keep the same strength for years together if not subjected to rough usage.

23. As will be more fully described hereafter, a magnet,

when disturbed from its position of rest in the plane of the magnetic meridian (sect. 28), is urged to return by a force which depends, among other things, upon *the moment of the magnet.* The moment of a uniformly and longitudinally magnetised bar is the product of its strength into its length. Coulomb measured the magnetic moments of magnets by means of the Torsion Balance. It consists of a glass cylinder,

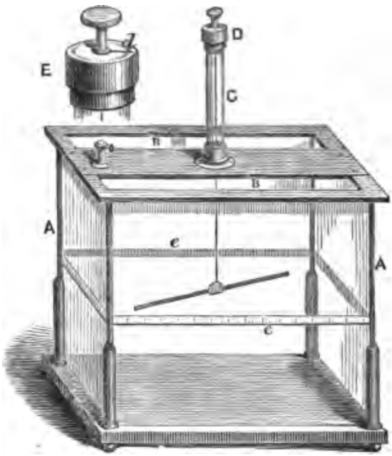


Fig. 18.

A, round or square, covered with a plate of glass, B, from the centre of which rises a tube, C, terminated by a plate, D, graduated on its margin (shewn on larger scale at E). Through the centre of D passes a short rod provided with an index, *d*, and terminating below in a hook to which is attached a fine wire. This carries a stirrup in which the needle to be experimented on is placed. When the wire is without torsion, the index should point to zero. A graduated strip of paper, *e*, *e*, is pasted on the cylinder on a level with the needle. When an experiment is to be made, the apparatus is so placed that, the magnetic axis (sect. 2) of the needle being in the plane of the magnetic meridian,

and the wire without torsion, the needle points to zero on e. The index, d, is then turned through an angle, θ, and this has the effect of deflecting the needle through an angle, α; consequently the torsion on the wire is $\theta - \alpha$, and the force of torsion is equal and opposite to the force tending to bring the needle back to the meridian. This is, at any one place and time, proportional to the magnetic moment multiplied by the sine of α. Knowing the force necessary to twist the wire through any angle, Coulomb determined by this method the moments of different magnets. He found that in cylindrical magnets of the same diameter, and in rectangular magnets of the same breadth and thickness, formed of the same steel, the moment was proportional to the length of the magnet.

With the help of the Torsion Balance he also ascertained the law of distribution of the magnetic intensity in magnets. The curve representing this intensity is given in sect. 2, fig. 2.

24. *Laws of Magnetic Attraction.*—Coulomb next investigated the laws of magnetic attraction. A long thin magnet was placed in the stirrup, and the instrument so arranged that the needle was in the magnetic meridian, and pointed to zero on e, while there was no torsion on the wire. A magnet identical with the suspended one was then inserted through an aperture in the glass plate, B, in a vertical position, so that one of its poles was near and in the same horizontal plane with the 'like' pole of the suspended magnet. The latter was immediately repelled, and when at rest, the repulsion between the two poles is equal to the directive force of the earth added to the force of torsion. These can be ascertained, and hence the repulsion due to the mutual action of the magnets at a distance equal to the chord of the angle of deflection can be measured. By twisting the wire through any angle, the distance between the poles is altered, and a new relation found between the repulsion and the distance. The angle through which the wire is twisted is equal to the sum of the readings of the needle and index.

By inserting magnets of different strengths Coulomb found how the repulsion varied with the strength of the repelling poles. The law he discovered is that *when magnets are so*

placed that two adjoining poles act on each other without the interference of the opposite poles—which happens very nearly when the magnets are long, thin, uniformly magnetised, and of hard steel—*their attraction or repulsion is in the straight line joining the poles, and is proportional directly to the product of the strengths of their poles, and inversely to the square of the distance between them.*

The strength of a pole is measured by comparing it with a conventional standard pole of unit strength. *Unit pole is a pole which points north and which repels another similar and equal pole placed at unit distance with unit force.* (For a discussion of unit force, see Chap. V.) A south pole is reckoned negative. Hence if m_1 and m_2 be the respective strengths of two poles, and d be the distance between them, and f the force, the above law may be expressed $f = \frac{m_1 m_2}{d^2}$. Thus, if the two poles are like, they will have the same sign, and f will be positive, shewing that there is repulsion. If one pole be a negative pole, f will be a negative quantity, indicating that there is attraction.

The laws of magnetic attraction may also be proved by causing a short and massive magnet, *sn*, to oscillate in a horizontal plane under the combined action of the earth and the pole of a fixed magnet, SN. The needle, *sn* (fig. 19), is suspended by a torsionless thread, so that in equilibrium it takes up a horizontal position in the plane of the magnetic meridian, and the number of oscillations is counted which it makes in a given time in each of three experiments—first, under the action of terrestrial magnetism alone; second, under the joint magnetic action of the earth and a thin magnet so long that its N pole has no sensible influence on the needle, when the magnet is held vertically in the magnetic meridian, so that its S pole is level with and two inches from the north pole of the needle; third, when the horizontal distance from S to n is increased to four inches. The force in each case is propor-

Fig. 19.

tional to the square of the number of oscillations, for the oscillations being small follow the law of pendulum motion. The number of vibrations in the three cases is 10, 36, and 20 respectively. The action of the magnet in each of the latter cases is evidently represented by the difference between the joint effect and that due to the earth alone; this in the second case is $36^2 - 10^2 = 1196$; and in the third case is $20^2 - 10^2 = 300$. The ratio of the forces is thus nearly 4 : 1; the distances of the attracting poles are in the ratio of 1 : 2. This shews that if the distance of the attracting poles be doubled, the attraction is reduced to one-fourth. Similarly, it is found that by trebling the distance we reduce the attracting force to one-ninth. In such a case the attraction is said to vary inversely as the square of the distance.

The law of the *action of magnets on soft iron by induction* was ascertained by Sir William Snow Harris in 1827. It is as follows: *The intensity of magnetism induced in the soft iron is directly proportional to the inductive force, and inversely as the distance.*

In the measurement of magnetic forces, repulsion effects are preferred to those due to attraction, when that is practicable; because attraction may be wholly or partially due to induction, whereas repulsion can only arise from the original forces in the magnets.

25. The strength of magnets is ascertained by the process described in sect. 24. A rough test of the strength of a horse-shoe magnet is given by the mass its armature can sustain against the attraction of the earth. Häcker found that if m is the mass of the magnet in pounds, and a a constant to be ascertained for the particular quality of steel, then the mass W which can be supported by the magnet is given by the formula $W = a \sqrt[3]{m^2}$. In his experiments $a = 12{\cdot}6$. Hence, a magnet of 2 oz. can support a mass of 3 lbs. 2 oz., whereas a magnet of 100 lbs. sustains only 271 lbs. Small magnets, therefore, are stronger for their size than large ones. It may be thus explained: Two magnets of the same size and power, acting separately, support twice the mass that one of them does; but if the two magnets

be made into one by placing them side by side with their like poles together, they no longer sustain the double of what either can sustain singly, because the action of the north pole of each induces a south pole in the other, and thus both the north poles are weakened: similarly the south poles are weakened, and the strength of the complex magnet is diminished. The same explanation applies to the diminution in strength of a complex magnet composed of more than two components. Now we may consider all large magnets as composed of several small ones whose mutual inductive action as above described renders the strength of the whole magnet much less than the sum of the strengths of its elements.

26. *Effect of Heat on Magnetism.*—A magnet loses in power as it rises in temperature, and as it cools it acquires again a portion of its lost strength, and the reverse takes place when it is cooled below ordinary temperatures. When it is raised to the same temperature several times, or when it is kept a sufficient length of time at it, it reaches a condition in which it suffers no further permanent loss by being again heated up to the same temperature. The change of intensity produced by ordinary changes of temperature is little, if anything. At a white-heat, a magnet loses permanently all trace of magnetism. When, however, it is again tempered and magnetised, it resumes its magnetic properties. It is found that soft iron, steel, and cast-iron, when temporarily magnetic —that is, when under induction—are capable of a greater intensity of magnetisation the higher their temperature, until they reach a dull-red heat; at that temperature it is the same for each, shewing that there the coercive force vanishes for these bodies. Beyond this, they become less susceptible to the influence of the magnet, and at a white-heat they are quite indifferent to it. The temperatures at which other substances affected by the magnet become indifferent to it, are different from that of iron. Cobalt is attracted by the magnet at the highest temperatures, and nickel loses this property at 662° F.

CHAPTER II.

TERRESTRIAL MAGNETISM.

27. *The Directive Action of Terrestrial Magnetism.*—The action of the magnet is so allied with the magnetism of the earth, that we cannot study the one apart from the other. The action of the earth on a magnet is simply *directive;* that is, it determines the position of the magnet relatively to the horizon, but produces no tendency to translation. This is usually shewn by making the centre of a magnetic needle rest on a piece of cork floating on water. The needle when so sustained comes round to a north and south position, but the float remains at the same point on the surface of the liquid. Another proof is that a needle has the same weight after as it had before magnetisation. The explanation is that the magnetic poles of the earth are so far distant from the magnet, that, practically, the north and south poles of the magnet are at equal distances from either of them. Accordingly, with whatever force the North Pole of the earth attracts the north pole of the magnet, it repels the south pole with an equal and parallel one, and hence its effect is reduced to that of a couple. The same is true of the action of the South Pole. The combined effect of the two couples is merely to determine the position in which the magnet will rest.

28. When a magnetic needle, uninfluenced by any body in its neighbourhood, is supported at its centre, so as to be free to turn in any direction, the needle takes up a definite position in which its magnetic axis coincides with the direction of the earth's magnetic force at that place. At most points on the earth's surface, the needle so suspended points approximately north and south. It is not horizontal, however, but is inclined to the horizon, or dips—the north pole being depressed in the northern hemisphere, the south pole in the southern. In order to determine accurately the direction of terrestrial magnetism it is necessary to use two needles, one free to turn about a vertical axis, and the other free to turn about a horizontal axis. The former, capable of rotating in a horizontal plane

only, assumes a definite position with reference to the horizon, and, when disturbed, oscillates about it. The vertical plane passing through the axis of the needle in this position is called the magnetic meridian; and the angle between it and the astronomical meridian is called the magnetic declination. If NS (fig. 20) be the direction of true north and south, and nCs be the position of rest of the needle, the angle NCn is the *declination*. It is east or west according as the magnetic north lies east or west of the true north.

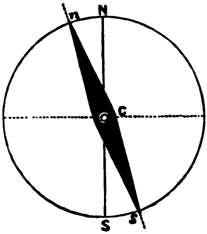


Fig. 20.

When the second needle is placed so that its axis is in the magnetic meridian, it also assumes a definite direction, generally inclined to the horizon. The angle which its magnetic axis makes with the horizon is called the *inclination*, or the *dip*. If NS (fig. 21) be the position of rest of a needle supported at its centre C, free to rotate in a vertical plane, and the plane of the paper be supposed to coincide with the magnetic meridian, and if aCb be a horizontal line, the angle NCa is the dip. The *intensity* of the earth's magnetic field at any point is the force with which unit pole would be acted upon there. The *declination*, the *inclination*, and the *intensity* are called the *magnetic elements*, and when they are known for any place, the terrestrial magnetic force is fully determined for that place.

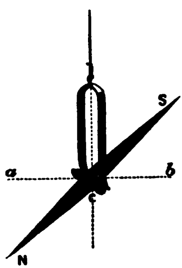


Fig. 21.

29. *Resolution of Total Magnetic Force.*—Let NS (fig. 22) be a needle adjusted to move in a horizontal plane. It is represented as lying in the magnetic meridian. The north pole of the magnet is attracted, and the south pole repelled, by equal forces. The magnetic force of the earth, represented by the lines NC and Sc, in magnitude and direction, tends, when acting on N, to draw it down, when on S, to send it up. The two equal and opposite parallel forces,

NC and S*c*, form with the needle a couple tending to make it rotate. To keep the needle in a horizontal position, the south end of it is made slightly heavier than the north end. The forces, NC and S*c*, may be resolved each into two others acting vertically and horizontally—that is,

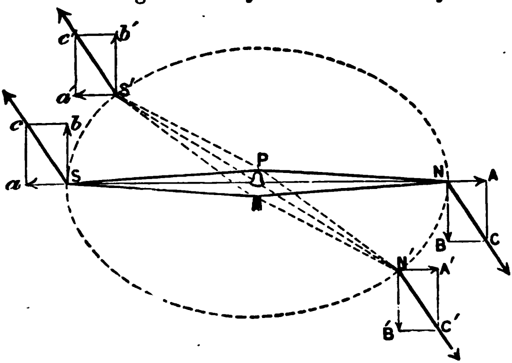


Fig. 22.

perpendicular to, and in the plane of, the needle's motion. The construction is exactly alike, so far as magnitude is concerned, at N and at S, but the direction of the components is opposite. The vertical components of the earth's magnetic force, which are alone concerned in determining the position of a needle moving in a vertical plane, are NB and S*b*. These are counteracted by the counterpoise. NA and S*a* are the horizontal components, and they alone are concerned in the motion of the needle in a horizontal plane. NA and S*a*, being equal and opposite, counteract each other. Suppose, now, the needle moved from its position of rest to that shewn by the dotted needle, N′S′. The earth's magnetism must act on N′ and S′ as it did on N and S, and consequently a similar resolution may be made. This resolution takes place in planes parallel to the former, which are perpendicular to the circle or plane in which the needle moves. The vertical components, N′B′ and S′*b*′, are counteracted as before by the counterpoise, but the horizontal components, N′A′ and S′*a*′, form a couple, tending to bring the needle back

to its first position. They act, however, obliquely on the needle, and to ascertain their effective force we must again resolve them as in fig. 23; along the magnetic axis and a

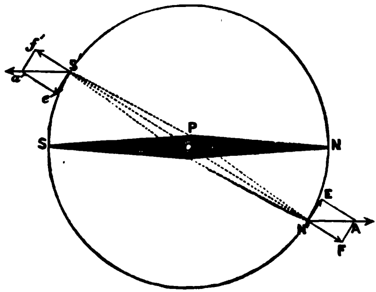


Fig. 23.

line perpendicular to it in the plane of the needle. The parts N'F and S'f' being equal and opposite, counteract each other, and the two effective parts, N'E and S'e', alone make the needle rotate.

Let (fig. 22) NC = T, the total intensity; NB = I, the vertical intensity; NA = H, the horizontal intensity; angle ANC = i, the angle of dip; then I = T sin. i, H = T cos. i, I = H tan. i.

INSTRUMENTS FOR ASCERTAINING MAGNETIC ELEMENTS.

30. *Declinometer.*—Instruments for determining magnetic declination are called declination needles or declinometers. In these instruments two things are essential—the means of ascertaining the astronomical meridian, and a needle for shewing the magnetic meridian. Fig. 24 represents a common form of the declinometer. Upon a tripod provided with levelling screws stands the pillar P, to which is fixed the graduated azimuthal circle CC. The compass-box B, with the vernier V, attached to it, moves on the azimuthal circle by means of a pivot at the pillar P. Two uprights, U, U, are fixed to the side of the compass-box, on the tops of which rests the axis of the telescope, T. A graduated arc, A, is fixed to the bottom of one of the uprights, and the angle of

elevation of the telescope is marked by the vernier on the arm E, attached to the axis of the telescope. A level, L, is also hung on the axis of the telescope, for adjusting it. Inside the compass-box is another graduated circle, F, the line joining the zero-points of which is parallel to the direction of the telescope line of collimation. All the fittings are of brass or copper; iron, of course, being unsuitable. The compass-box and telescope move round as one piece on an axis passing through the centre of the azimuthal circle. When an observation is to be made, the instrument is levelled, the needle is set free, and the telescope is pointed to a celestial object whose position with regard to the astronomical meridian is known at the time of observation, or can be found by calculation. If the telescope with the compass-box be then turned the proper number of degrees on the azimuthal circle, until its axis is in the astronomical meridian of the place, it is evident that the reading of the needle on the inner circle will give the declination. For example, if, when the telescope is in this position, the north end of the needle stand at the zero-point of the inner circle, the declination would be 0°; but if it lie east or west of this point, the declination is shewn by the degree at which the needle stands. To insure that the reading obtained is that of the magnetic axis of the needle—for the magnetic may not coincide with the geometrical axis of the needle—it is necessary to take two readings—one when the needle is in its usual position and the other when it is inverted. In the two positions the

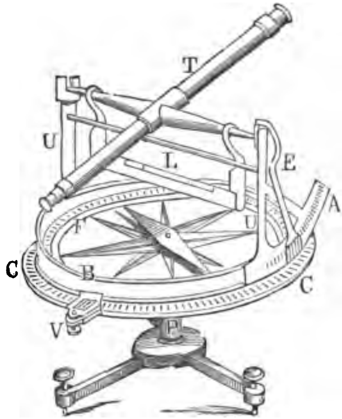


Fig. 24.

magnetic axis has the same direction—that of the magnetic meridian and the deviations of the axis of figure are of equal amounts but on opposite sides of the magnetic axis. Hence the mean of the readings is the true one, and half the difference is the correction which must be made in future observations when the needle is used in one position only.

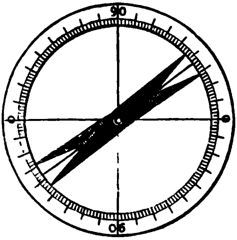


Fig. 25.

31. A declinometer like the one just described can only give the declination approximately. To be quite exact, the needle would require to be very long, so as to allow the divisions of the circle on which it moves to shew very small angles. This, however, would be attended with the objection that a very long needle is more difficult to move than a short one, so that what we should gain in the number of divisions on the circle we should lose in the sensibility of the needle. Gauss's apparatus obviates this objection. Fig. 26 gives a general idea of the action of his instru-

Fig. 26.

ment. NS is a magnetic bar, suspended in a stirrup by a wire or a few untwisted filaments of cocoon silk sufficient to sustain its weight, which is a few pounds. The silk is more suitable than the wire, as its torsion affects the results to a less extent. It is inclosed in a glass case (not shewn in the figure), to shield it from currents of air. On the rod by which the bar is suspended, a small mirror, M, is fixed, the plane of which is at right angles to the magnetic axis of the bar. A few yards from the bar, a theodolite, T,

and a scale, S, about a yard long, are placed, the one a little above, the other as much below the mirror, so that the divisions of the scale may be seen reflected at the cross-wires of the theodolite. A small plummet hangs down from the object-glass of the theodolite, the thread of which stands in front of the zero or middle point of the scale, which is approximately perpendicular to the magnetic meridian. When a magnetic bar is hung in this way it never keeps still, but is constantly making small oscillations, like a pendulum. The direction about which it is oscillating at any time is the magnetic meridian at that time; and the mean of the readings taken when the needle is at the two extremities of its oscillation gives the reading of the magnetic meridian. Suppose that, as the result of such observations, we find that the needle oscillates about a point, P, one inch from the zero, and that the distance of the scale from the mirror is 15 feet. We can easily learn from the trigonometrical tables that the angle PMO is 19′ 6″, for

$$\tan. \mathrm{PMO} = \frac{\mathrm{PO}}{\mathrm{MO}} = \frac{1}{180};$$

or we can obtain approximately the same result by considering that the arc is the same fraction of 360° as 1 inch is of $2 \times 3{\cdot}1416 \times 15$ feet, the circumference of the circle. It can be shewn by an easy geometrical construction that the apparent angle is twice the angle that the mirror or the magnet describes, so that the real deflection of the needle in this case is 9′ 33″. The observation thus obtained is as correct as if a needle 30 feet in length had moved through an angle 9′ 33″, or described an arc of half an inch on a 30-foot circle. To find the absolute declination at any time, we have first to find, as above, the angle which the magnetic meridian makes with the zero position of the scale, which is so placed as to coincide with the optical axis of the theodolite; then the angle which the optical axis of the theodolite makes with the astronomical meridian. The sum of these, taken with their proper signs, gives the absolute declination. To obtain continuous observations, which are extremely valuable, a lamp is substituted for the theodolite, and a small spot of

light from it is reflected by the mirror to a cylinder rotating uniformly round a horizontal axis by means of clockwork, and covered with sensitised photographic paper. Wherever the light falls a mark is made, and so a continuous line is traced, by means of which we can tell the position of the needle at any time. A self-recording system on this principle, invented by Mr Brooke, is adopted in almost all observatories.

32. The *Mariner's Compass* is also a declinometer, for it must be always used with reference to the true north of the region where it acts. It consists of a needle nicely poised on a point, with a cross-bar of copper or brass at its middle. The needle and bar support a card above, which is marked with thirty-two equidistant points (as in fig. 27). The north and south points of this card lie directly over the magnetic axis of the needle, so that the card, and not the needle, indicates these cardinal points to the observer. The whole is inclosed in a brass or copper bowl. This is placed within a ring, which moves by two pivots in another ring, itself supported by two pivots at right angles to the other two. These two rings are called the *gimbals*. The compass-box and card thus supported remain always horizontal, whatever be the motion of the vessel in which it is placed. Inside the compass-box a vertical black line is marked, called the lubber-line, which is in the axis of the ship or in the line of the ship's motion. The point of the card that lies at the lubber-line shews how the ship is going.

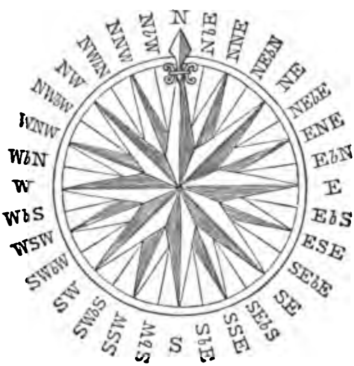


Fig. 27.

33. The great difficulty connected with the use of the mariner's compass arises from the disturbing influence of the ship's magnetism, part of which is permanent and may be considered constant, and part—that due to the soft iron—is

temporary, and varies with the intensity and dip of the earth's magnetism. This difficulty is particularly felt in iron vessels, where the deviation of the needle is frequently so considerable as to render the compass almost useless. Various means

Fig. 28.

of obviating this have been suggested; one of these is to place bars of soft iron or magnets near the compass, in such a position as to cause a contrary disturbance to that of the iron of the ship. This is found to answer well in iron ships plying between British and continental or North American ports; but where the magnetic latitude changes considerably, as in the Australian passage, such an arrangement is found to be worse than useless, because the induced magnetism of the vessel changing with the latitude causes an ever-varying deviation of the needle. It has likewise been

suggested to place a compass as a standard at the mast-head, where it would be comparatively free from the attraction of the vessel, by which the ship's course might be shaped, the ordinary compass being used merely to give immediate direction to the steersman. Another course which is adopted is to place a compass so high above the deck as to clear the bulwarks, and allow the bearings of a distant object on shore or a heavenly body to be taken while the ship's head makes a complete circuit. In this way, the deviation caused by the iron of the ship in all different positions may be ascertained, and afterwards taken into account.

34. Sir William Thomson has recently invented a compass (fig. 28) which is free from most of the defects of those in ordinary use. It consists of a thin aluminium ring connected by silk threads to an aluminium boss, which is supported on an aluminium cup with a sapphire cap, poised on an iridium point (fig. 29). Small thin magnets are fixed on two parallel threads, and slung from the aluminium rim by four silk threads or fine copper wires; the card itself consists of strong thin paper properly divided, and the central parts cut away. Hence it is very light—the 10-inch compass being only one-twentieth of the weight of ordinary cards of the same size—friction in turning is thus reduced, and the point of support lasts much longer. Since most of its heavier parts are at the circumference, the time of a vibration is increased, and the compass is thus rendered much steadier. The corrections required on board ship are easily applied. It is found in practice to be steadier, quicker, and more accurate than any other compass.

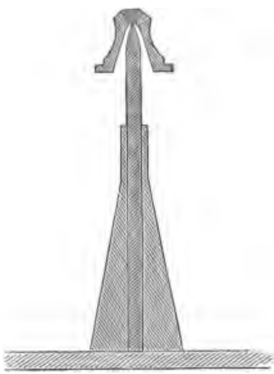


Fig. 29.

35. *Dipping Needle.*—The dip of the magnetic needle at any place can be ascertained with great exactness by means of

the dipping needle, fig. 30. It consists of a graduated circle, AA, fixed vertically in the frame FF, and moving with it and the vernier V, on the horizontal graduated circle HH. This last is supported by a tripod furnished with levelling screws. At the centre of the circle C, there are two knife-edges of agate, supported by the frame, and parallel to the plane of the circle. The needle, NS, rests on these knife-edges by means of fine polished cylinders of steel, which are placed accurately at the centre of the needle, and project at right angles from it: so adjusted, the needle moves with little friction. It is so made, moreover, that before being magnetised it remains indifferently in any position; after magnetisation, therefore, the dip which it shews is wholly due to the magnetic influence of the earth. It will be seen from fig. 22 (sect. 29) that when a needle is capable of vertical motion, the earth's magnetism will swing the needle round until it coincides as nearly as possible with the direction of the earth's magnetic force. When the needle is in the magnetic meridian, the coincidence is complete. The moment of the couple NC and Sc (fig. 22) is in that case zero. When the needle moves in a plane at right angles to

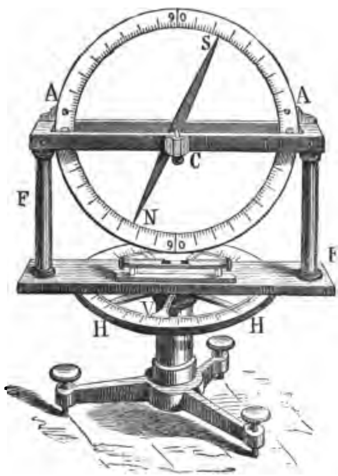


Fig. 30.

the magnetic meridian, the vertical component alone can affect its position, and makes it hang vertical. In this case the moment of the couple NB and Sb (fig. 22) vanishes. Between these two positions the needle shifts from the vertical position to that of the direction of the dip, and is always more inclined to the horizon than when

in the meridian. We have thus two ways of finding the meridian. When the needle points to 90° or is vertical, it is at right angles to the meridian, except at the magnetic equator (sect. 41); and by moving the vernier over 90°, we can place it in the meridian. Again, that plane in which the inclination of the needle is least, is the plane of the meridian, and the dip is the angle which it then makes with the horizon. In making observations with the dipping needle several sources of error have to be neutralised, such as deviation of zero-point of vertical circle from horizontality, false centering and deviation of axis of form from magnetic axis.

36. *Intensity.*—The sources of error involved in working with a magnet capable of rotation in a vertical plane only, are so great, that to determine the intensity of terrestrial magnetism at any place, the practice is to determine the horizontal component from which the total intensity can be obtained when the dip is known. A magnet is suspended in a stirrup by a silk fibre so as to be free to turn about a vertical axis. It is then made to vibrate under the mutual action of its own magnetism and the terrestrial magnetism of the place, and the number of vibrations it makes in a given time is ascertained. As this depends on the horizontal intensity so long as the magnet and the thread remain exactly the same, the time the magnet takes to make one vibration, is a measure of the horizontal intensity in terms of the moment of the magnet. As the moment of the magnet is liable to alter with a change of temperature or of the inductive action of the earth, and from other causes, the time of a vibration would alter with any one of these. In order that a measure independent of the moment of any particular magnet or of temperature or any other circumstance, and therefore called absolute, may be obtained—the same magnet is employed to deflect a second similar magnet from the plane of the magnetic meridian. The apparatus is so arranged that the deflecting magnet is fixed so as to be always in a line at right angles to and passing through the centre of the deflected magnet. The distance between their centres is known or can be measured, and the angle between the magnetic axis of the deflected magnet when at rest and the magnetic meridian gives a measure

of the ratio of the horizontal intensity to the magnetic moment of the deflecting magnet. The time of vibration in the previous experiments gave a measure of the product of these two quantities, and therefore the horizontal intensity can be determined absolutely from the two experiments. Thus, the average horizontal intensity at Kew for 1875 was 1·7915 metric units, which signifies that a south pole one milligramme in mass, and of unit magnetic force, would, supposing it were insulated and free to move in a horizontal plane, acquire in one second a velocity southward of 1·7915 millimetres per second. Or we may express it by saying that a mass of a milligramme acted on for one second by a force equal to the horizontal intensity would acquire a velocity of 1·7915 millimetres per second. In British units expressed in feet, with the mass of a grain instead of a gramme, the same quantity is 3·8855.

37. The horizontal intensity at any place is continually undergoing changes. These are small in amount, and to measure them a very sensitive arrangement is necessary. This is obtained by the use of Gauss's Bifilar Magnetometer, of which a rough representation is given in fig. 31. It consists essentially of a magnet suspended by two wires. The line joining their upper extremities is generally not in the magnetic meridian; and if they were supporting a bar of wood or copper, of dimensions similar to those of the magnet, the wires would be in a vertical plane which would also intersect the supported bar in the line, joining the points to which the supporting wires were attached. But the magnet, under the influence of terrestrial magnetism, tends to place itself as nearly in the magnetic meridian as possible, and consequently twists the wires out of the vertical plane. This has the effect of raising the magnet, and

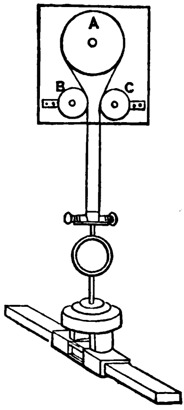


Fig. 31.

thereby the tension of the wires is increased, which, with any torsion given to the wires by the rotation of the magnet, opposes the couple due to the horizontal intensity tending to place the magnet in the magnetic meridian. The increase of tension and the torsion corresponding to any position of the magnet can be calculated, and hence by observing the position which the magnet assumes at any moment, we have a measure of the horizontal intensity. The sensitiveness of the apparatus can be altered by changing the length of the wires, their distance apart, &c. Like the declinometer, the magnetometer has a mirror attached to it, and a scale, and the position of the magnet can be photographically registered.

38. *Magnetic Charts.*—The magnetic elements have been ascertained with great care at different portions of the earth's surface. The knowledge thus obtained has been embodied in magnetic charts, in which lines are drawn through those places for which the declination is the same; and similarly for the dip and intensity. The lines of equal declination are called isogonic lines; those of equal dip, isoclinic; and those of equal intensity, isodynamic lines. As the magnetism of the earth is subject to a slow secular variation, such charts are only true for the time of observation. The chart fig. 32 was drawn up by Sir Edward Sabine for the year 1840, and gives an approximate view of the lines of equal declination for that year. The change since 1840 has been small, so that an isogonic chart for the present time would differ but slightly from it. The chart sufficiently explains itself. Attention may, however, be given to one or two points. The declination is marked on each line. Thus the line passing through England, for instance, is marked 25°, and that passing north-west of the British Islands 30°. At places through which these lines pass, the needle points in a direction west of the true north, in the one case 25°, in the other 30°; and at places between the two lines, including Scotland and Ireland, the direction of the needle is intermediate. Thus in Dublin the declination was in 1840 about 27° 30′. The westerly line of no declination cuts off the eastern corner of South America, proceeds to North America, which it traverses, and ends in the north at Boothia. The easterly

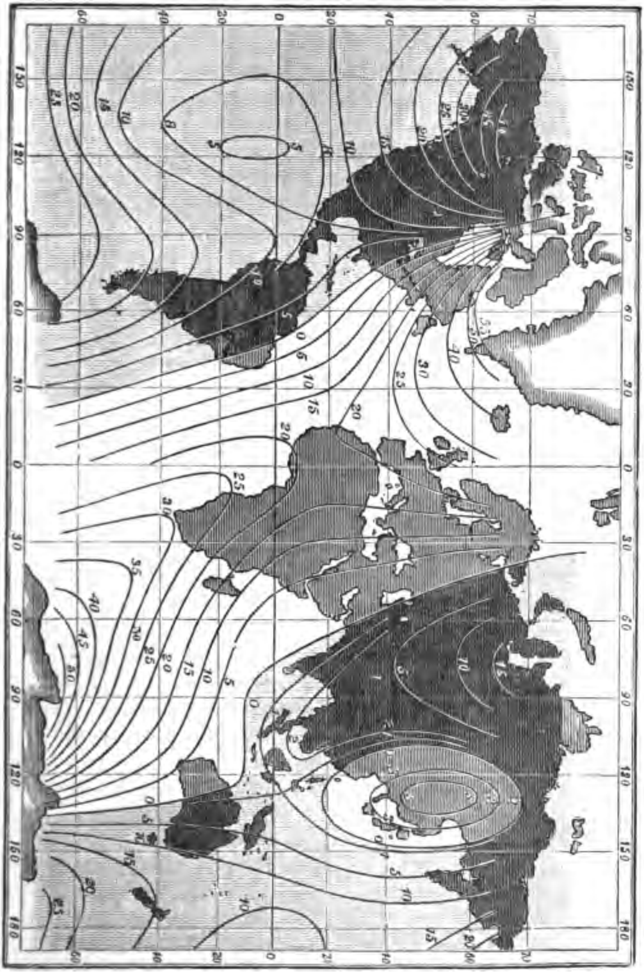


Fig. 82.

line of no declination enters Europe in the north of Russia, crosses the White Sea, the east of Russia, Persia, and the Arabian Sea; then turns eastward, and cutting off the west of Australia, passes southward. The untinted portion of the chart between these two lines contains all places where the declination was westerly. It includes the east of the two Americas, the Atlantic Ocean, the whole of Europe and Africa, and the west of Asia and Australia. The rest of the earth, which in the chart is tinted, has an easterly declination. An elliptic space in Eastern Asia, left white, has a westerly variation, and forms an exceptional region in the eastern magnetic hemisphere.

It will be seen that the lines converge in the north of North America, and to the south of Australia. So far as experience goes, and so far as the most matter-of-fact theory (Gauss's) teaches, the convergence in both cases is towards a point. The point in North America is called the *north magnetic pole*, and that to the south of Australia the *south magnetic pole*. At these points, then, all isogonic lines converge, and a compass needle lies indifferently in any position.

39. According to the same theory, if the isogonic lines were traced on a globe, instead of, as here, on a map in Mercator's projection, they would form irregular curves, approximating to circles, on the northern and southern hemispheres. Each circle in the north would contain in its circumference the north magnetic and geographical poles, the portion of the circle on the one side of the poles being in the hemisphere of westerly declination, and the other in the easterly. The sum of the angles marked on the two portions would amount to 180°, the larger segment having the smaller angle. The same conformation of circles would be visible at the south pole. These two sets of circles proceeding from both poles, would meet each other at the equatorial regions, and when they began to overlap, would run into each other, forming irregular curves passing through the four poles. This conformation can be traced more particularly on the white part of the chart. In the North and South Atlantic, the curves are seen approaching each other, and proceeding from the region of the north and south poles.

The last two circles that approach without touching are marked 20°. The circles marked 15° would overlap; but instead of doing so, they run into each other, and make two continuous curves, forming together a figure resembling the outline of a sand-glass. The same union, with a less contraction in the middle, is seen in the lines marked 10° and 5°.

40. The isogonic lines, as seen from the chart, form a somewhat complicated system. This arises from the fact, that we refer the indications of the needle to the geographical poles, which are, so far as we know, arbitrary or extraneous as regards terrestrial magnetism. Admiral Duperrey constructed charts to shew the declination on a somewhat different principle from that made use of in the isogonic chart. In his chart lines are drawn so that the tangent at each point of any one of them is the direction in which the needle points at that place—that is, the direction of the curve is everywhere that of the magnetic meridian, and hence the lines are called magnetic meridians. They are found to converge like the lines of force of a bar magnet towards two points—one in the N. hemisphere, about 70° N. lat. and 98° W. long., and the other in the S. hemisphere, about 75° S. lat. and 138° E. long. On the same chart are drawn lines which always intersect the meridians at right angles, and are called magnetic parallels, and which also are approximately circles.

41. The chart fig. 33, also by Sabine, represents the isoclinic lines or lines of equal dip for 1840. In the upper part of the chart, which is left white, the north end of the needle dips; and in the lower part, which is tinted, the south end of the needle dips. The amount of dip is marked on each line. Thus, the line passing through the centre of England is marked 70°. A dipping needle, at any place cut by the line, is inclined 70° to the horizon. The line 75° passes to the north of the British Isles. In Ireland and Scotland, therefore, the dipping needle has an inclination greater than 70°, and less than 75°. The line marked 0° is the line of no dip; at any station on it the dipping needle is horizontal. This line is called the *magnetic equator*. It will be seen that it is not coincident with the geographical equator; it is not even a great circle of the earth,

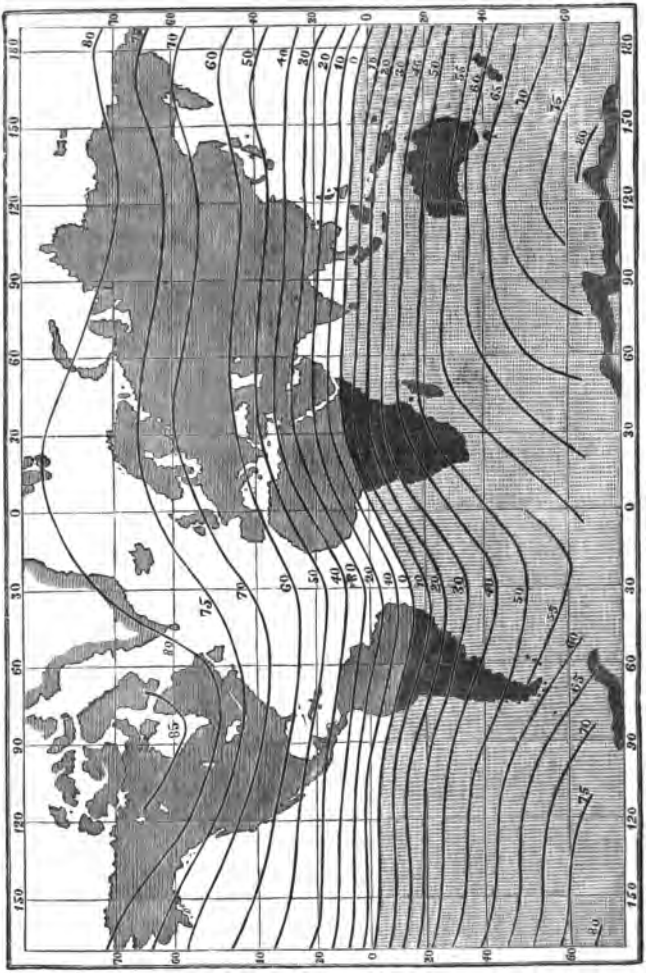


Fig. 33.

but an irregular curve cutting the equator in two points, one near the west coast of Africa, and the other in the middle of the Pacific Ocean. The points on the earth's surface where the dipping needle stands vertical, and where, in consequence, as before mentioned, the compass needle lies in any direction, are called the magnetic poles. The north magnetic pole was found in Boothia Felix by Sir James C. Ross at 70° 5′ N. lat. and 263° 14′ E. long. According to Gauss's calculation, it should have been at the time (1831) some 3° north of this point. From observations made at Hobart Town, the nearest station to it, the south magnetic pole should lie in 66° S. lat. and 146° E. long. These points are not diametrically opposite each other like the geographical poles. If the lines of equal dip were drawn on a globe, they would form round the magnetic poles a system of irregular circles, somewhat resembling that of the parallels of latitude round the poles of the earth. The irregularities of the magnetic curves are to a certain extent attributable to the irregular distribution of temperature, which greatly depends on the distribution of land and water.

42. We do not add an isodynamical chart, as it would engross too much space. Sir Edward Sabine's Dynamical Chart, along with the isogonic and isoclinic charts, will be found fully engraved and explained in Johnston's *Physical Atlas* (new edition). From this chart we learn that the magnetic intensity is least in the vicinity of the magnetic equator, and increases as we approach the magnetic poles. The lines of equal intensity, though running much in the same direction as the lines of equal dip, are neither coincident nor parallel with them. The line of least intensity, itself not an isodynamic line, runs nearly parallel to the magnetic equator, but lies, except in the western half of the Pacific, a few degrees to the south of it. We thus learn that the changes in direction and intensity do not march together. We should fancy that at that point or points on the earth's surface where the dipping needle stood erect, we should be nearest to the centre of free magnetic energy, and that there the force would be greatest; but this is not the case. The point in North America where the intensity is greatest is situated to the west of

Hudson's Bay, about 52° N. lat. and 92° W. long. But this is not the only point of maximum force in the north magnetic hemisphere. There is another, which was found by Hansteen in 1828, in Eastern Siberia, about 118° E. long. and 60° N. lat. This maximum point is weaker than the American, in the proportion of 100 to 107 (Sabine). According to Gauss, there can only be one maximum point in the southern hemisphere, and it is stronger than either of the other two. It lies north-east of the south magnetic pole, and its intensity is 137 (Gauss) compared with 107, that of the principal northern centre. At none of those points does the dipping needle stand erect. This want of coincidence of the points of vertical dip and of maximum intensity has led to some confusion in the use of the term magnetic pole; some writers meaning by it a point of vertical dip, and others a point of maximum intensity. In adopting the former definition, we are only adhering to the popular meaning of the word, and to the opinion of Gauss, perhaps the greatest authority on the subject. Some of the best English authorities, however, attach to it the latter meaning.

43. Although the total intensity increases as we go northwards or southwards from the line of least intensity, the horizontal intensity diminishes. This arises from the fact that the horizontal intensity depends partly on the dip; the greater the dip, the less the horizontal intensity (sect. 29). Hence, the compass needle, which is affected by the horizontal intensity only, oscillates more sluggishly as we leave the line of least intensity. A dipping needle, for instance, oscillates faster at London than at Calcutta, because the total intensity which affects it is greater at London than at Calcutta; but with a compass needle it is the reverse, because the horizontal intensity is greater at the latter than at the former station.

44. *Variations of the Needle.*—The magnetic elements do not remain constant in the same place, but are subject to continual small periodic variations. These are regular and irregular. Under regular variations are included *secular*, *annual*, and *diurnal* variations. The secular variations

take centuries for their completion. The following list of the declination and dip at London in different years will give an idea of the secular variations for these elements:

Year.	Declination.	Year.	Inclination.
1576	11° 15′ easterly.	1720	74° 42′
1657—1662	0° 0′, no declination.	1780	72° 8′
1760	19° 30′ westerly.	1800	70° 35′
1815	24° 27′ 18″ westerly. Maximum.	1830	69° 38′
1850	22° 29′ 30″ westerly.	1850	68° 48′
1865	21° 6′	1865	68° 9′
1875 (average)	19° 33′	1875 (average)	67° 47′

From these observations it will be seen that in 1576, when the earliest reliable measurement of the declination was made, it was 11° 15′ easterly. This divergence from the true north diminished till 1657—1662, when it pointed to the true north. It then varied westward till 1815, when it stood farthest from the true north. Since then the needle has been veering eastward, and coming nearer to the north. At present, the annual decrease of declination at London is nearly 8′. At this rate it would take rather more than eighty-four years before the compass needle shifts through a whole point. The magnetic history of London does not apply to other places; each place, so far as has been ascertained, having a magnetic history of its own. Thus, in Paris, the time of no declination was 1669; and of maximum declination, 1814; the latter amounting to 22° 34′ west. At the Cape of Good Hope the variations are in the opposite direction; for from about 1607, when the magnetic and geographical meridians there coincided, the north end of the needle has been pointing more and more west. At present the declination is 32° W. At Hobart Town again the declination is easterly and is increasing slowly.

From the observations of the dip, we find that it has been gradually decreasing for the last hundred and fifty years. The annual decrease of dip is at present about 2′·6. From the time observations have been taken of the declination and dip until now, we are far from having completed a cycle of change in either, and it is matter of

speculation how long that may take. Every place, according to Barlow, appears to have its own magnetic pole and equator. Magnetic intensity has been observed for so short a time that little as yet is known of its secular variation. The average total magnetic intensity at Kew, for 1875, was 10·276 British magnetic units (foot, grain, second), or 4·738 metrical units (millimetre, milligramme, second). At present, the horizontal intensity is increasing in Europe, but that may arise partly from decrease of dip.

45. The magnetic elements are subject also to changes, which have a yearly and a daily period. In describing these shortly we shall limit ourselves to the changes affecting declination, as these are of most general interest. As regards the annual variation of declination, it would seem to depend on the position of the sun; for we find that for places in the northern hemisphere the declination is to the east of the mean from May to October, reaching a maximum in August, and is to the west of the mean from November to April, with a maximum in February. In the southern hemisphere the simultaneous variations are in the opposite direction. It will be noticed that the maxima in each hemisphere occur at the hottest and the coldest periods of the year. The range of the annual variation at Greenwich is about 2′ 25″. The extent of the oscillation varies from year to year, and seems to depend upon the state of the sun's surface, as do probably all magnetic phenomena. It is found that the years in which the sun's spots attain a maximum are those in which the declination range is a maximum, and the years of minima also coincide. Balfour Stewart and others have shewn that if curves be drawn—one representing the condition of the sun as regards sun-spots, and the other the declination range for the same period—every well-marked point in the former has a corresponding point in the latter. One of the remarkable features in these curves is that every declination point occurs about six months later than the corresponding sun-spot point. Moreover, it has been shewn that there is apparently some connection between the positions of the planets Mercury, Venus, and Jupiter, and the magnetic conditions of the earth.

46. The mean *diurnal variation* for Kew is shewn in fig. 34

(kindly furnished by Mr G. M. Whipple of the Observatory). This irregular line indicates the course of the north end of the needle. A rise of this line indicates a change of the north end to the east, a fall a change to the west. The interval between two horizontal lines corresponds to a deflection of the needle of 1′. The line marked *o* is the magnetic

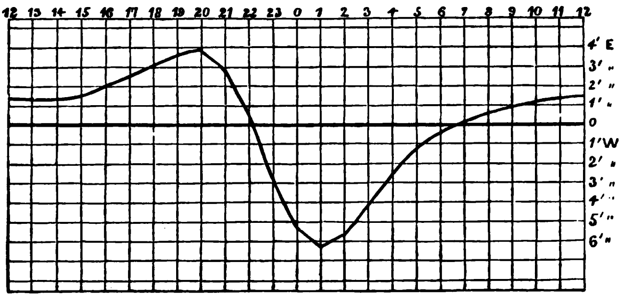


Fig. 34.

meridian, or the mean daily position of the needle. The interval between two upright lines corresponds to an hour. The course begins at twelve at night, and ends at twelve the following night. From the figure we see that at twelve at night the magnet is 1½′ east of the mean position, and continues nearly in the same position, with only a slight westerly deviation, till fifteen hours (three in the morning), when it veers eastward. At twenty hours (eight in the morning) it reaches its furthest east point. From eight in the morning till one in the afternoon, it makes a sweep of 10′ towards the west, and then stands about 6′ to the west of the mean. After one, it goes westward till midnight, when it again begins the same course. The needle stands in its mean position a little after ten in the morning, and a little before seven in the evening. The course here described is the average course for the year. Observations prove that the extent of the diurnal range is different in different months. In May, for instance, the average range between the extreme points is 12′, which is the maximum range for the year;

and in December, when it is a minimum, it is only 5′ 28″. The diurnal changes here described for Kew are much the same all over the north magnetic hemisphere. The range, however, is different at different places, becoming less as the equator is approached. At stations on the equator itself, the variations do not vanish, as was formerly supposed, but correspond to those in the northern hemisphere from the vernal to the autumnal equinox, and with those in the southern hemisphere during the remainder of the year. They nearly vanish at the equinoxes. In the southern magnetic hemisphere the daily motions of the needle take place much in the same way as in the northern hemisphere, only the south pole takes the place of the north pole, and the direction of the deflections is reversed. The correspondence, and at the same time opposition, of the southern hemisphere is also shewn from the time of maximum and minimum range. When the sun is in the northern signs of the zodiac, the range is a maximum in the northern, and a minimum in the southern hemisphere; and when the sun is in the southern signs, the reverse takes place.

47. The *irregular variations* are those which break in upon the regular march of the diurnal variation without in the main altering it. Instead, for instance, of the needle steadily going westward from 8 A.M. to 1 P.M., as shewn in fig. 34, it makes, when affected by irregular variation, deflections eastward as well as westward, although it in the main moves westward; so that the line between these hours, instead of being comparatively straight, would be an irregular zigzag. These disturbances of the mean course are sometimes considerable, amounting even to one or two degrees in extreme cases. On some days the mean diurnal course is much disturbed, on others very little; but it is never quite free from them. It has been found that places of the same longitude have similar disturbances at the same time; that those on opposite sides of the globe, or differing by 180° of longitude, have disturbances equal in amount but opposite in direction; and that those situated 90° west or east of the disturbed regions have little or no disturbance. The appearance of auroras is invariably accompanied by magnetic irregulari-

ties, and their effect extends far beyond the regions where they are visible. Earthquakes and volcanic eruptions have also a marked effect in this way. Humboldt gave the name of *Magnetic Storms* to these irregular disturbances. Sabine has found that the frequency of magnetic storms is greatest every eleven years at the same time that the spots on the sun are most numerous.

48. *Theories of Terrestrial Magnetism.*—The earliest theory was that suggested by Gilbert, in which it is supposed that a magnet in the middle of the earth extended from one magnetic pole to the other. On this supposition, the general phenomena of terrestrial magnetism may be accounted for—a needle, both by declination and dip, must point to the poles. This must always remain, from its simplicity, the popular theory on the subject. In consistency with his theory, Gilbert considered the north pole of the magnet to be a south pole, as he took the north pole of the earth for his standard north pole. If this theory were correct, the magnetic equator would be a great circle of the earth, and the magnetic poles would be 90° from it, which is far from the case. It is only a rough approximation to a just theory.

Halley endeavoured to supplement Gilbert's theory, by supposing two magnets of unequal strength crossing each other at the earth's centre to be the cause of terrestrial magnetism. The theory of the two magnets or four poles was ably defended by Hansteen.

Barlow considered that the earth acted on the needle as if currents of electricity traversed it from east to west. He imitated its action by wrapping a wire in parallel coils round a wooden globe, and causing a galvanic current to pass through it. Each turn of the wire represented a magnetic parallel, and the two ends of the coil the magnetic poles; and to complete the analogy, the globe was movable on an axis, which stood in the same relation to the ends of the coil as the astronomical axis to the magnetic poles of the earth. When a small needle was placed on the globe, its declination and dip bore a striking resemblance to those of a needle similarly situated on the earth's surface. The objection to this theory is the

difficulty of accounting for the origin of such currents in the earth. To meet this, some suppose the earth to be a huge thermo-electric pile ; as the heat of the sun falls on one side of it, currents are there generated which travel round the globe. But how, again, it may be asked, are the conditions of thermo-electricity implemented by the materials of the earth? This question still remains to be answered. The close connection between temperature and magnetism is shewn by the diurnal variation of declination, the epochs of which closely correspond with those of the daily temperature, and by the fact that the isodynamic and isothermal lines manifest a marked correspondence. Sir David Brewster has also shewn that there are two centres of maximum cold in the northern hemisphere, which are situated near to the two intensity poles.

Gauss did not start from any simple supposition of one or two magnets giving rise to the magnetism of the earth, nor did he assert or deny its electric origin. Considering the whole earth as magnetic, he aimed at determining how it must act as a whole at the different points on its surface. In order to make the equations he obtained theoretically, express the distribution on the earth, the magnetic elements of eight stations at a sufficient distance from each other on the earth's surface had to be ascertained and substituted in these equations. This done, from the longitude and latitude of any station he considered himself prepared to deduce its magnetic elements. The magnetic charts which he sketched, though founded on the imperfect observations to which he had access, are singularly in keeping with fact, and go far to establish the correctness of his reasonings.

CHAPTER III.

CHRONOLOGY OF MAGNETISM.

49. The property of the loadstone to attract iron appears to have been the only fact in the science of magnetism known to the ancients. The compass is a comparatively modern discovery; it was certainly known in Europe in the 12th century, the first reference to it being made in a manuscript poem by Guyot de Provins, now in the National Library of France. The Chinese, according to some, were acquainted with it as early as the 4th century. The discovery of the change in declination at different places is generally attributed to Columbus, and was one of the many important observations of his memorable voyage across the Atlantic. Robert Norman, an instrument-maker in London, first discovered the dip of the needle in 1576. He was led to it by finding that needles nicely balanced before magnetisation had to be slightly loaded on the south end, to keep them horizontal after being magnetised. The first really important contribution to magnetism as a science was the *Tractatus de Magnete* by Dr Gilbert of Colchester, physician to Queen Elizabeth. It was published in 1600. He first used the word poles with reference to magnets, and gave the first theory of terrestrial magnetism, namely, that of the single magnet. Halley, the astronomer-royal, published his theory of the four poles in 1683. In 1688 and 1689, at the expense of government, he made two magnetic voyages, the results of which he embodied in his charts of the lines of equal declination, published in 1701, which were the first magnetic charts ever published. In 1722 the diurnal variation was discovered by Graham, the celebrated instrument-maker of London. Canton determined it in 1759. About the middle of the 18th century, armatures began to be used, and various new processes of magnetisation were found out. Knight in 1745 invented divided touch, which was afterwards improved by Duhamel (sect. 21); and Mitchell in 1750 double touch, afterwards improved by Æpinus (sect. 21). Brugman in 1778 discovered that cobalt was attracted and that bismuth was repelled by the magnet. Coulomb in 1789

discovered the law of the distribution of magnetism on a magnetic bar, and the law of magnetic attractions and repulsions. The first inclination chart was published by Wilcke, at Stockholm, in 1768. Humboldt inaugurated the present system of careful observations of terrestrial magnetism by taking comparative measurements of the magnetic elements at Peru and Paris in 1799—1803. Hansteen's work on the *Magnetism of the Earth* (sect. 48) was published at Christiania, 1819 ; in 1826 he published the first isodynamic charts. Barlow in 1831 suggested the electric origin of terrestrial magnetism (sect. 48) ; and in 1833, introduced correcting plates of soft iron for ships. In 1831, Sir James C. Ross came upon the north magnetic pole. In 1835, stations were established throughout Europe, and the observations were published by Gauss and Weber, 1836. Duperrey's observations, 1822—1825. Gauss in 1833—1840 perfected his theory. In 1837, Sir Edward Sabine published an isodynamical chart of the whole globe. Diamagnetism was discovered by Faraday, 1845. Observations were made in 1840—1854 at stations throughout the British empire by British officers, under the direction of Sir Edward Sabine. In 1855, Tyndall shewed that a diamagnetic body assumed a polarity similar in action but oppositely directed to that of a magnetic body when under the action of magnetic force.

In recent years the advances made have been chiefly in tracing the connection between terrestrial magnetism, the condition of the sun's surface, and the positions of the planets and moon, reference to which has been made in the text. In 1876, Sir William Thomson invented a new mariner's compass.

Part II.—FRICTIONAL OR STATICAL ELECTRICITY.

CHAPTER IV.

GENERAL PHENOMENA.

50. *Fundamental Fact of Electricity.*—More than two thousand years ago it was known that when amber—whose Greek name is *elektron*—is rubbed with a woollen substance, it acquires the property of attracting light bodies. Till comparatively recent times, not much more was known about electricity—the name given to the influence supposed to communicate this property of rubbed amber; but during the past hundred years or so, a very great increase has been made to our knowledge of this branch of Natural Philosophy.

51. *Electric Pendulum.*—The elementary facts of electricity are illustrated by the *electric pendulum* (fig. 35). A glass rod placed on a suitable stand supports a fibre of unspun silk, to the end of which a pith-ball is attached. If a tube of glass be rubbed with a dry silk handkerchief, and brought near the ball, the ball is at first briskly attracted, and after contact it is as briskly repelled; and if the tube be then moved towards it, it moves off, always keeping at a distance. The ball being so affected, or charged, as it is called, a rod either of shell-lac or sealing-wax, after being rubbed with flannel, and brought into the neighbourhood, attracts it very briskly, and after contact repels it exactly as the glass had done. If the glass tube be again

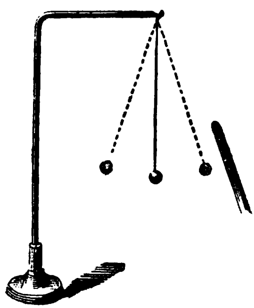


Fig. 35.

taken up, and rubbed a second time, if necessary, the ball will be affected by it as it was by the sealing-wax, being first attracted, and, after contact, repelled. The same series of attractions and repulsions would have taken place if we had begun with the sealing-wax instead of the glass tube. From these experiments we learn that when glass is rubbed with silk, and sealing-wax with flannel, they, like amber, become endowed with the property of attracting, and subsequently repelling, light bodies, and are then said to be electrified or in a state of electrification. Moreover, we see that although the glass attracts the ball at first, it repels it immediately after contact. The same is true of the wax. Again, when the ball is in a condition to be repelled by the glass rod, it is attracted by the wax; and when repelled by the wax, it is attracted by the glass. What the one repels, the other attracts.

We may infer from these experiments, what will be fully confirmed by later experience, that other bodies besides amber possess its property: that there are two kinds of electrification, with similar but opposite properties—that shewn by the glass, and that shewn by the wax. Also, that the repulsion of the ball after contact with the glass or the wax, is due to a communication of part of their electricity to it; and, that bodies with the same kind of electricity repel one another. Lastly, since the ball, when electrified with the same electricity as the glass, is attracted by the electrified wax, and when electrified like wax, is attracted by electrified glass, we see that bodies charged with unlike electricity attract one another.

52. It was customary to distinguish these two kinds of electricity as *vitreous* or *resinous*, according as the electrified body behaved like the glass or the sealing-wax. As these names seem to imply that only the one kind of electricity is got from glass, whereas either kind can be obtained, it is better to speak of the vitreous electricity as *positive*, and the resinous as *negative*. These names have the advantage of shewing the opposite characters of the two kinds of electrification. They admit, moreover, of a very convenient contraction, namely, the algebraic + for *positive*, and − for *negative*.

We are taught by the above experiments, that *bodies electrified either positively or negatively, attract neutral bodies and bodies with the opposite electrification, but repel those with the same kind of electrification;* and that *the electrical condition can be communicated from one body to another.* The former of these statements is sometimes put thus—*Like electricities repel one another, unlike electricities attract.* A neutral or unelectrified body is one which is not charged with electricity; the pith-ball, before any experiments were made with it, was an instance of an unelectrified body.

53. *Nature of Electricity.*—To explain electrical phenomena, different theories have been proposed as to the nature of electricity. It has not been positively decided yet what electricity is, but the most favoured idea is contrary to its being material. The best known theories treat it as a substance existing in the form of two fluids or one. In the former, every non-electrified body has an enormous and equal quantity of each of the electric fluids in it, and they are then said to be neutral, fixed, or combined; so great is this quantity, that by no possible electrification can a body be entirely deprived of either kind. These fluids have no mass nor weight, nor any other properties of fluids, save that of mobility, and attraction and repulsion. They are not, as in the corresponding magnetic theory, confined to the molecules of the body, and can be separated—one fluid being drawn to one part of the body, and the other to the opposite. They may also pass from one body to another. The molecules of either fluid repel like molecules, and attract those of the other fluid, with a force varying inversely as the square of the distance between them. A body is charged positively (or negatively) by having an excess of the positive (or negative) fluid, or a deficiency of the negative (or positive) one. The excess of the one fluid in a body over the other is called the Free Electricity. A positive electrification may be produced in a conductor either by a transference of a quantity A of positive electricity to it, or of an equal quantity of negative electricity from it, or by a simultaneous transference of positive electricity to it and negative electricity from it, the sum of these two quantities being equal to A.

The single-fluid theory supposes that all bodies are composed of two kinds of material particles—one ordinary matter, the other the electric fluid. The former has all the properties of matter; the latter has only mobility, and attraction and repulsion. The particles of matter repel other particles of matter, but attract the particles of the fluid with a force varying inversely as the square of the distance between the particles. The particles of fluid have similar properties; but the attraction between any given quantities of unlike molecules is slightly greater than the repulsion between the same quantities of like molecules when the other conditions are the same; consequently there is a slight resultant attraction between an amount of matter in combination with an equal amount of the fluid and another similar combination of matter and fluid. When equal quantities of matter and fluid are present in a body, it is non-electrified, and the matter and fluid are then said to be combined. When more fluid than matter is present, the body is positively electrified; when there is a deficiency of the electric fluid, the electrification is negative. There may be an excess of the fluid in one part of a body, and a deficiency in another, and then the former is positive, the latter negative.

54. We may further illustrate the laws stated in sect. 52 by another very instructive series of experiments. A glass vessel, A (fig. 36, *a*), in the form of a cylindrical or globular bottle, is provided with a tightly-fitting cork, B. Through B passes a metal (usually brass) rod, C, fixed by sealing-wax. At its upper extremity the rod carries a metal disc, D, and to its lower extremity are attached two rectangular pieces of gold-leaf, E, three or four inches long by one broad, hanging face to face. To keep the air dry, a dish containing sulphuric acid is sometimes placed inside. Two strips of gold-leaf or tinfoil are usually pasted on the inner side of A, in such a position that the leaves, E, will touch them when they diverge to a great extent. The apparatus is called an Electroscope, for by its aid the kind of electricity with which a body is charged, can be ascertained.

Having rubbed the glass rod briskly, bring it towards the plate of the electroscope. As it approaches, the leaves

will diverge (fig. 36, *b*), shewing repulsion, which is due to their being similarly electrified. While they are divergent, touch the plate with the finger (fig. 36, *c*); the leaves will immediately collapse. Remove the finger, and then the glass rod: the leaves will again diverge (fig. 36, *d*), owing to their

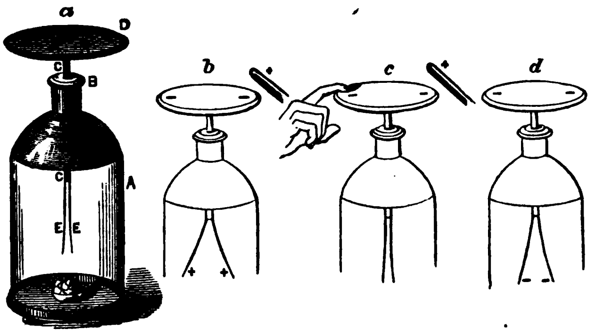


Fig. 36.

being again similarly electrified. Now bring the glass rod near, the leaves collapse; nearer still, they diverge again; remove the rod a little, they collapse; remove it further, they diverge again, and remain divergent, shewing that there is now a charge in the electroscope. Bring the electrified wax near, the leaves diverge still more. Take the wax away, they resume their former divergence. If we begin with the wax rod, we have a similar series of phenomena. The explanation is this. At first the plate and leaves are unelectrified. When the electrified glass rod is brought into the neighbourhood, it attracts the opposite electricity to the plate and repels the like electricity to the leaves; hence the leaves repel each other. When the plate is touched by the hand, the experimenter, and with him the earth, becomes electrically a part of the electroscope, and the positive electricity is repelled by the glass rod into the earth through the body. The negative electricity is retained chiefly in the plate by the attraction of the glass rod. When the finger and then the rod are removed, the negative electricity spreads over the plate and leaves, and

the leaves consequently again diverge; when the glass rod is brought near again, it attracts the negative electricity to the plate; there is thus no electricity in the leaves, and they collapse; when brought nearer, the rod separates more of the neutral electricity in the plate and leaves, drawing the negative electricity to the plate and repelling the positive electricity to the leaves, which again diverge. When the electrified wax is brought near, it repels the negative electricity in the plate and leaves to the lower extremities of the leaves, and hence makes them diverge more than before.

55. This experiment shews that we can charge a body without touching it with one already electrified, and we are then said to charge it by *induction.* But it will be noticed that in doing so we charge it with the opposite kind of electricity to that possessed by the inducing body. The two bodies were separated by air, which does not, as we see from this experiment, allow the electricity of the glass to pass to the electroscope. In that capacity the air is called a *Dielectric.* We see also how the electroscope may be used to shew whether a charged body, A, is positively or negatively electrified. Because, if we charge the electroscope inductively by the glass rod, a body charged positively and brought near will make the leaves collapse; but if charged negatively, will make them diverge.

56. These laws may be further illustrated by using two electric pendulums placed near one another. Charge both the balls with the glass or the wax, then they will repel each other; or charge one of the balls with the glass rod, and then allow the other to touch it; the first will communicate a portion of its charge to the second, and they will repel each other, but not so much as before. If they are charged, the one with the glass rod and the other with the wax, they will attract each other. We see from these experiments that the effect is somehow dependent on the amount of electrification, and hence we may speak of a quantity of electricity, which we can measure by the effect it produces.

57. *Conductors and Non-conductors.*—The electric pendulum was described in sect. 51 as consisting of a glass stem with a ball of pith attached to it by a silk thread. With a metal

stand and a cotton thread or a wire, we could not make the experiments described, because any electricity given to the ball by contact would have instantly been conducted to the ground by the wire and stem. The silk thread and the glass rod offer resistance to the passage of the electricity, and hence are called non-conductors. Bodies possessing this property are often called insulators, since they may be used, as in this case, to support electrified bodies without allowing their electricity to escape. Copper, silver, and the metals are the best conductors; gases, paraffin, glass, vulcanite and resinous substances are among the best insulators. It must be observed that these terms are entirely relative. Every substance conducts electricity more or less, and every substance resists the passage of electricity to a greater or less degree; there is no perfect conductor, and no perfect insulator. When a substance is spoken of as being a conductor, it is generally meant that it is a good conductor. (The name Conductor is generally applied to bodies of good conducting material, which are mounted on insulating stands for the purpose of holding charges of electricity.) Good conductors allow the electricity to move freely over and through them, and if a charge be given to one part of a good conductor, it is instantly spread over the whole surface. A charge given to a bad conductor takes a long time to distribute itself, and, in fact, in many cases is practically confined to the particular portion of the body where it was originally put.

The following series classifies the more common substances according to their conducting powers, beginning with the best, and ending with the worst conductors: The metals, graphite, sea-water, spring-water, rain-water; alcohol and ether, dry wood, marble, paper, straw, ice at 32° F.; dry metallic oxides, fatty oils, ice at − 13° F., phosphorus, lime, chalk, camphor, porcelain, leather, dry paper, feathers, hair, wool, silk, gems, glass, agate, wax, sulphur, resin, amber, gutta-percha, caoutchouc, shell-lac, ebonite, water-vapour, gases.

An increase of temperature has in the case of the metals the effect of lessening the conducting power, whilst it has the opposite effect in almost all other substances. Glass becomes a conductor at a temperature below that of boiling

water, and wax, sulphur, amber, and shell-lac become so when fused.

58. *Insulation.*—When a conductor is placed on supports which prevent the electricity communicated to it from passing into the ground, it is said to be *insulated.* The insulating material usually employed in the construction of electrical apparatus is glass, which is hard, durable, and easily worked, and, could its surface be kept dry, would be one of the best non-conductors. In frosty and in very dry weather, glass insulates well; but at all other times it becomes coated with a thin, scarcely visible, layer of moisture, which very considerably impairs its insulating power. In order to insure dryness, it is necessary to warm electric apparatus before use. Water-vapour, in the form of a gas, is non-conducting, and when it can be kept from condensing on the glass, does not affect its insulating power. The deposition of moisture is much lessened by coating the glass with shell-lac, which is done by painting the glass when hot with shell-lac varnish. Green glass, which contains no lead, is better adapted for the construction of electric apparatus than flint glass, and does not condense moisture to the same extent. Sir William Thomson has tested the insulating power of glass by preserving charges of electricity in hermetically sealed glass bulbs for years. Ebonite, a rigid preparation of vulcanised india-rubber, is much superior to glass as an insulator. It is of this substance that india-rubber combs are made, which in dry and frosty weather make the hair crackle with electricity. Even with the best insulators, and with dry air, it is not possible to maintain undiminished the charge which a body receives. There is invariably a loss, arising chiefly from the particles of air or dust becoming charged, and carrying off the charge; and partly, perhaps, from the insulators, even the best of them, being imperfect non-conductors. In all exact experiments it is necessary to ascertain the rate at which the charge diminishes, and to take it into account in estimating results.

59. The term *electrics* used to be applied to those substances which, when held in the hands and rubbed, become electric; and *non-electrics,* to those which do not. The distinction is

an unnecessary one, for if proper arrangements are made, it can be shewn that all bodies become electrified when rubbed. In the case of conductors held in the hand, the electricity is no sooner excited than it is conveyed by the body, which is a good conductor, to the ground ; while in the case of non-conductors, it remains on their surface. When a metal rod is rubbed with a silk handkerchief, no electricity is shewn by the rod if it is held in the hand ; but if held by a glass handle, it is at once seen to be electrified on being brought near an electroscope. In the first case, the hand conveys the electricity of the rod to the ground ; but in the second, the glass prevents this discharge. The rod is truly an electric in both cases ; non-electric is a term applicable to very few, if any, substances.

60. In the description of the preceding experiments nothing has been said about the condition of the rubbers. It is found, when proper precautions are taken, that the silk handkerchief employed to rub the glass acquires the negative electric state, and the flannel rubber of the sealing-wax the positive. This cannot, however, be clearly shewn when the experiment is performed as above described, for the rubbers are in each case held in the hand, which, being a conductor, carries off a great portion of the electricity produced on them, so that they give feeble, if any, evidence of electrical excitement. As the rods are non-conductors, and are held only by their extremities, the electrification of the untouched portions suffers almost no diminution. If vulcanised india-rubber cloth, however, be used instead of the silk handkerchief, the rubbing side of the cloth shews negative electricity. The opposite electricities of the rubbing surfaces are best shewn when the rubber as well as the rubbed surface is insulated. When two similar discs—one of glass, the other brass covered with silk—held by insulating handles, are rubbed together, so long as they are kept touching, no electricity is shewn : but when they are separated, the former shews positive electricity, the latter negative electricity. The negative and positive conductors of the electric machine (sect. 142) illustrate the same principle. From the most careful observations attending the production of electricity, we are

led to conclude that *when a quantity of one kind of electricity is produced, as much of the opposite electricity is produced.* In no case is one electricity produced without an equal quantity of the other. This will be more fully considered later on.

61. It has been found by experiment that the relative nature of the rubbing and rubbed surfaces determines the kind of electricity which each assumes. Thus, if glass be rubbed with cats' fur instead of with silk, its electricity is negative instead of positive. This shews the impropriety of calling one kind of electricity vitreous. In the following list, each body, when rubbed with any one preceding it, is electrified negatively; with any one succeeding it, electrified positively: cats' fur, smooth glass, linen, flannel, feathers, wood, paper, silk, sealing-wax, shell-lac, ground glass. When two pieces of the same material are rubbed together, the colder or the smoother becomes electrified positively. An apparently small difference in the nature of the surface or the temperature or colour often entirely changes the position of the substance in the above list. Where the temperature of the positive body can be raised sufficiently, it is found that the relative position of the two substances can be changed; the one usually electrified negatively becoming positively electrified, and the other being negatively electrified. Metal filings rubbing against a plate of the same metal produce negative electricity in themselves, and positive electricity in the plate. When a white silk ribbon is rubbed with a black one of the same texture, the white one becomes positively electrified. When two portions of the same ribbon are rubbed together, the one longitudinally and the other transversely, the latter is always negatively electrified. A plate of glass becomes positively electrified when a stream of air is directed against it from a pair of bellows. The amount of electricity developed is apparently not proportional to the amount of energy expended in rubbing.

62. *Processes of Electrification.*—There are other means of developing electricity besides friction. In general, everything that tends to disturb the molecular condition of bodies tends to produce electricity. *Cleavage*, *pressure*, and *change*

of temperature, more especially in crystalline minerals, are frequently attended with the development of electricity.—The electricity of cleavage is shewn by rapidly cleaving a plate of mica, when one of the divided faces shews positive electricity, the other negative electricity. A feeble luminosity also marks the separation when made in the dark. If the laminæ are pressed together and again separated, they again shew the same electrification as before. Several other minerals possess the same property. The light that is seen to accompany the breaking of loaf-sugar and sugar-candy in the dark is generally attributed to the electricity of cleavage.—Haüy found that when a piece of calc-spar is pressed between the fingers, it becomes positively electrified, and remains so for days together. Fluor-spar, topaz, mica, arragonite, quartz, and other minerals, assume one or other electricity when pressed. When two discs, one of cork, the other of caoutchouc, are pressed together by insulating handles, and separated, the cork is found to be electrified positively, the caoutchouc negatively. The same is also true of cork and coal, shell-lac, zinc, and warm calcareous spar; but cork becomes negatively electrified when pressed against dry fur, flannel, skin, fluor-spar, and cold calcareous spar. A slice of cork and a slice of orange observe the same relation in similar circumstances. When in the latter case the separation is suddenly made, we obtain a greater effect than when it is made slowly, from which we learn that conducting surfaces when pressed together shew no excitement, probably from the recombination of both electricities at the instant of their production. In fact it is evident that unless one of the substances be a non-conductor it will be very difficult to obtain a charge of electricity by means of pressure.—Tourmaline offers the most remarkable illustration of the electricity got by change of temperature. While a crystal of this mineral is being heated, it shews positive electrification at one end of its principal axis, and negative at the other. If it be divided when in this condition it is found that each of the halves is electrified in the same way as the whole. It thus manifests an electric polarity, like the magnetic polarity of the magnet. When the rise in

temperature ceases, for an instant it loses polarity, and then as it cools it assumes the opposite polarity to that it had before, being negative now where formerly it was positive. Below 50° F., and above 302° F., tourmaline seldom shews electric properties. Topaz, boracite, and several other minerals resemble tourmaline in their action under heat. The electricity thus developed by heat is sometimes called pyro-electricity. There are other sources of electricity, of which we shall afterwards treat, such as chemical action, motion of magnets, heating of a circuit composed of different metals, &c.

63. When water is evaporated, it is usually found that the vessel from which it is evaporated is electrified, and that the vapour has the opposite electrification. The electrification apparently depends upon the nature of the other substances present in the water. If it contains free oxides of such metals as potassium, sodium, calcium, the water becomes positively electrified: if there is a soluble acid or a carbonate chloride, the water is negatively electrified. When the water is perfectly pure, it does not become electrified on evaporation.

64. Sir William Armstrong invented an engine by which electricity can be generated by the friction of steam. It consists of a boiler on insulating supports, which supplies steam to tubes which pass through a condenser, D (fig. 37), filled with cold water. This condenses the steam partially, and it then escapes through nozzles, A, so formed as to cause much friction between the escaping steam and the sides of the nozzles. A comb, P, provided with a series of points is placed in the jets of steam, and collects the electricity and conveys it to the prime conductor, B. In ordinary circumstances the prime conductor was charged positively and the boiler negatively, and large sparks were obtained. Faraday investigated the action of the Hydro-electric Machine, and shewed that the small drops of water produced by the partial condensation were essential to the production of electricity: that electricity was due to the friction between these drops and the sides of the nozzles, for on changing the material with which they were lined, the

amount or the kind of electricity produced was changed: when the water was made a conductor, by dissolving in it any salts, acids, &c., no electricity was produced : when turpentine or any fatty substance was added to the water, the boiler was

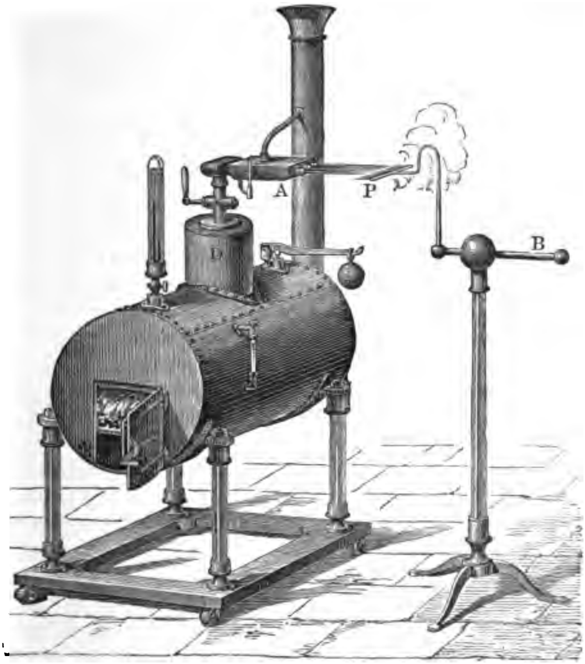


Fig. 37.

charged positively, the prime conductor negatively: the production of electricity increased with the pressure of the steam. A current of moist air driven through the nozzles charged them negatively, but carried positive to the points: there was no electricity produced when perfectly dry air was used.

CHAPTER V.

DYNAMICAL PRINCIPLES.

65. To understand the phenomena of electricity and magnetism, a knowledge of the elementary terms and principles of dynamics is necessary, and for the convenience of the reader a short epitome of them is given here.

66. *Units of Measurement.*—Every quantity is measured in terms of a standard or unit, and its value is expressed as a multiple of that unit. For example, the unit of length usually adopted is either the foot or the metre, or some multiple of one or other, and lengths are expressed as being so many feet or metres. Thus a mountain is said to be 4567 feet high. In the measurement of time the second is usually adopted for the standard; an average day is so many seconds. So a sovereign is a unit in the measurement of money: a degree in the measurement of angles.

67. A body at any instant is in some definite position, but if it change from one position to another it is said to move or to be in motion. A body in motion has at any instant a definite rate and a definite direction of motion. A ship, for example, is said to sail at ten knots per hour in a north-easterly direction. *Velocity* is the rate of motion; but it involves the idea of direction as well as that of magnitude. Hence a straight line may represent the velocity of a body at any instant—the length being proportional to the magnitude, and the direction representing the direction of motion. Thus AB would represent a velocity twice as great as, and in a direction perpendicular to, the velocity represented by CD. *Velocity* is *uniform* when the rate of motion does not change, that is, when equal spaces are traversed in equal portions of time. It is measured by the number of units of length passed over in unit of time.

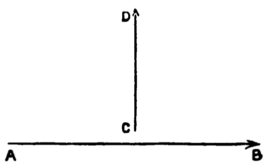


Fig. 38.

The velocity of sound in air at the temperature of freezing water is 1093 feet per second—that is, sound travels 1093 feet in one second. Unit velocity is the velocity of a body which passes over unit of length in unit of time. Thus if a foot and a second are the units of length and of time respectively, unit velocity is that of a body moving over one foot in one second. The velocity of a body may be changed either by increasing or diminishing the rate of motion, or by altering its direction. AB, A′B′, A″B″ represent the velocities of three

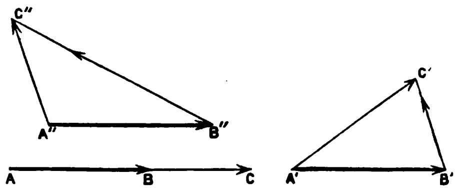


Fig. 39.

bodies at one instant of time, and AC, A′C′, A″C″ their velocities at another. In the first case the velocity has changed in magnitude only, in the second it has changed in direction only, and in the third both in magnitude and direction; and the changes of velocity are represented by BC, B′C′, B″C″.

68. *Acceleration* is the rate of change of velocity per unit of time, and may take place either in the direction of motion or not. inertia

69. *Mass* is the quantity of matter in a body. The *Unit of mass* generally adopted is either the quantity of matter in a grain, a pound avoirdupois, or a gramme. (The weight of a body is due to the gravitation attraction of the earth for it, and is always proportional to the mass.)

70. *The Momentum* of a body, or its quantity of motion, is measured by the product of the velocity of the body into the mass. The momentum of a given mass is changed when the velocity is changed. *Unit momentum* is the momentum of unit mass moving with unit velocity. In British units, a pound moving with a velocity of one foot per second, or half an ounce moving at thirty-two feet per second, or two pounds

moving at half a foot per second, has unit momentum. So a mass of one pound moving with a velocity of 32·2 feet per second, has 32·2 units of momentum. In the centimetre gramme second system (written C.G.S.) the unit momentum adopted is that of one gramme moving with a velocity of one centimetre per second. *Change of momentum* is measured by the product of the mass and the change of velocity, and may be due to a change either in the direction or in the rate of its velocity.

71. *Force* is any cause which tends to alter a body's natural state of rest or of uniform motion in a straight line.

A force is measured by the momentum it generates in its own direction in unit of time. The force is then said to be measured in Kinetic or Absolute units. The absolute measures are so called because they are independent of any variable such as the intensity of gravity. They are all expressible in terms of the fundamental units of mass, space, and time.

72. *Unit Force* is that force which generates unit momentum in unit of time. One very familiar instance of a force is the weight of a body. If a pound be allowed to fall at Edinburgh under the action of its own weight—the attraction of the earth for it—it acquires in one second a velocity of 32·2 feet per second. Hence the weight of a pound at Edinburgh acting for one second generates 32·2 units of momentum, and is therefore equivalent to 32·2 British units of force in absolute measure. Again a gramme acquires, after falling freely for one second at Paris, a velocity of 980·9 centimetres per second, and therefore its weight is 980·9 C.G.S. units of force. Hence if M be the number of pounds in a given mass, and g the number which expresses the weight of unit of mass in absolute measure at the place, Mg is the weight.

73. It is often very convenient to measure a force in terms of the weight it can support. This is called the Statical or Gravitation system of units. The objection to this method is that the standard by which the forces are compared has not the same value at different parts of the globe. We could by proper apparatus measure the attraction of one magnet for another at a specified distance, by the weight necessary to

counteract the attraction. Let this be done in Britain. Repeat the experiment at the equator. There, supposing the magnets to remain exactly the same, we would find that the same counterpoise would no longer neutralise the attraction. It would be too little, because the weight of the counterpoise is less at the equator than in Britain. In other words, although the attraction between the two magnets remains the same, its value as measured in gravitation units is different in the two places ; for the weight of a mass varies with the latitude and also with the height above the sea-level. This variability in results renders the measurement of forces in gravitation units useless for purposes of comparison, unless the latitude and the level be specified. To reduce forces measured in gravitation units to absolute measure, it is necessary to multiply the value of the force in gravitation measure by the weight in absolute measure of unit of mass at the place. Thus a force equal to the weight of six pounds at Edinburgh is in absolute units equal to $6 \times 32{\cdot}2 = 193{\cdot}2$, if $32{\cdot}2$ be taken as the value of g at Edinburgh.

74. Forces, like velocities, may be represented by straight lines—the direction and length of the line representing the direction and magnitude of the force. Thus DA and DB represent two forces acting at the point D in the directions indicated by the lines, and with magnitudes proportional to their lengths.

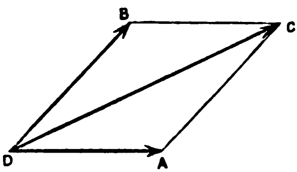


Fig. 40.

When two or more forces act at a point simultaneously, one force can always be found equivalent to them all. It is called the *Resultant Force.* In the example above, it is represented in magnitude and direction by the line DC, found by drawing BC equal and parallel to DA and joining DC. The resultant of any number of forces represented by all the sides of a polygon but one taken in order, is represented by that one taken in the opposite direction.

A force may be resolved in any two directions at right angles to one another—and these are called the *components*

of the force. Thus the components of AB in the directions AC and AD are found geometrically by drawing through A and B lines parallel to the two directions—the components being represented by the parts intercepted—that is, by AC and AD. AC is equal to AB multiplied by cosine BAC, and AD is equal to AB multiplied by sine BAC.

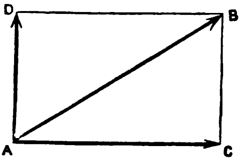


Fig. 41.

75. *Work* is done when resistance is overcome, and the quantity of work done is measured by the product of the resisting force and the distance through which that force is overcome.

Unit of work is the work done when unit force is overcome through unit space.

76. When work is done opposite to the direction in which a force acts, it is said to be done against the force; when it is done in the direction in which the force acts, the force is said to do work. As an example, take the case in which the attraction of the earth for a body is the resistance to be overcome. The amount of the resistance is measured by the weight of the body, and the direction in which it acts is vertical. Therefore, to measure the work done against gravity when a body is raised from one level to another, we must multiply its weight by the height—the weight being the force overcome, and the height the distance through which it is overcome. The ordinary *gravitation unit of work* is the work required to raise a pound one foot, hence called a foot-pound. In raising a hundredweight of coals 100 feet, the work done is 112×100 foot-pounds. The same amount of work is required to raise half a hundredweight 200 feet, or a quarter of a hundredweight 400 feet, or five hundredweight 20 feet. But as the work done in raising a mass through any height depends upon the intensity of gravity at the place, it is necessary, in order to convert this into absolute units, to multiply the gravitation measure by the value of g at the place. Thus if M be the number of pounds, and h the height through which they are raised, and g the value of gravity at

the place, Mh is the gravitation measure of the work, Mgh the same in absolute measure. In estimating in these examples the work done against gravity, no account is taken of the path by which the body was raised. It may have been a load of stones dragged from a deep quarry up a long series of inclined roads, or it may have been an equal load of coals brought up the shaft of a pit by machinery. Or as in the case of firing into a fort above the level of those attacking it, it may have been necessary to project the shell to a height above the fort, so that it may drop into the fort in its descent. In one case we go over a long path before we attain the level we wish to reach, in another case a comparatively short one, and in a third case we go beyond the level and partially return, but the work done is estimated solely by the product of the weight lifted and the vertical space through which on the whole it is lifted—that being the direction in which we have overcome the resistance. So long as the weight is the same, the work done is proportional simply to the difference of level between the original and the final positions. There may be more tear and wear by one path than by the other; but that is not due to gravity, and at present we are concerned only with the work done in overcoming gravity.

77. Similarly we do work in compressing air, into a cylinder for instance. If we know the average resistance which we had to overcome during the process—or what is the same thing, the average pressure it was necessary to employ—and the distance through which the piston has been pushed, the work done is measured by the product of these two quantities.

78. It has been shewn that two bodies repel each other when charged with the same kind of electricity, and attract each other when charged with opposite kinds. Suppose that an insulated conductor A is charged with a known quantity of positive electricity, and that another conductor B is charged with a known quantity of negative, they will attract each other. If we remove B a short space further *from* A, work will be done against the electrical forces, which can be measured by the product of the distance through which B has been removed and the average value of the force exerted.

Exactly the same amount of work would be done if, B being removed altogether, a third body C, similar to B, charged with a quantity of positive electricity equal to B's negative charge, were brought from B's second position to its first.

As another example, take the case where a weight is transported from one place at any height above the level of the sea to another place at the same height. In such a case there is on the whole no work done against gravity, even though in transit it may have been necessary to take the body over a very high pass, because the positions at the beginning and the end of the operation are at the same level. This may perhaps be better understood by considering that however much work was required to be done against gravity to raise the body to the highest point, an exactly equal amount of work was done by gravity when the body descended to the old level. In all cases where there is no displacement in the direction in which the force acts, there is no work done against or by the force.

79. Work is also done when the rate of a body's motion is changed, and it is then measured by half the product of the mass of the body and the difference of the squares of the initial and final velocities. If a body of mass M increase its velocity from v_1 to v_2, the work done in overcoming the inertia is $\frac{1}{2}M(v_2^2 - v_1^2)$. Again in the case of a body of mass M, falling freely from rest under the action of its own weight, and acquiring a velocity v, the work done by gravity is $\frac{1}{2}Mv^2$. This can be shewn to be equal to Mgh, where h is the height fallen through, and g is the weight of unit mass at the place. It was stated in sect. 76 that this is the work necessary to raise the body to its former position against the earth's attraction.

80. *Energy is the power a body has of doing work.* There are very many forms of energy. Thus a raised stone can fall, and in doing so may raise other stones, or do work in other ways; a wind can root up trees, drive a windmill, or bring ships from one port to another; gunpowder can propel bullets or blast rocks; a horse can draw wagons; a stream can

carry ships; coal can generate heat—itself a form of energy—which may be employed to do work in various ways; a current of electricity can generate heat, decompose liquids, give light, noise.

81. *Potential energy* is energy in virtue of position. Any raised mass is an example of a body possessing potential energy. Because of its weight it can fall: in doing so it will perform work of some kind. In the case of the monkey of a pile-driving engine it will drive a beam into the earth. In the case of the weight of a clock it will keep the works in motion by overcoming the friction; or in the case of a pond of water it will turn an overshot mill-wheel by making one side heavier than the other. Compressed gas is another instance of a mass possessing potential energy. If confined in a chamber provided with a movable piston, it can press out the piston against external resistance, as in the case of any steam, air, or gas engine. Gunpowder has potential energy, for by giving play to the chemical affinity of its ingredients we can make it explode, and so do work in a variety of ways. Other instances, due to chemical affinity, are seen in combustion, as of coal, and the oxyhydrogen blowpipe.

82. The *mutual potential energy* of two bodies in any relative position is the amount of work obtainable from their mutual repulsion or attraction by allowing them to separate from that position to an infinite distance apart (in the case of repulsion), or to come from an infinite distance to that position (in the case of attraction). The potential energy always diminishes in the direction of the resultant force. In cases of repulsion, as of two similarly electrified bodies, the potential energy increases as the bodies are brought nearer each other: the opposite is the case in attraction.

The *potential* at any point due to any attracting or repelling body or distribution of matter, is the mutual potential energy between it and a unit of matter placed at that point.

83. *Kinetic energy* is the energy a body has in virtue of its motion, and is measured by half the product of its mass into the square of its velocity. As examples of kinetic energy we have a bullet propelled from a rifle, a running stream, winds,

tides. When a body M is thrown vertically upwards it rises to a height, and so does work $= Mgh$. It can be shewn that h is equal to $\frac{v^2}{2g}$, where v is the velocity of projection. In other words, the height the body rises or the work it does is proportional to the square of its velocity. Hence, when the velocity is trebled, the height the body will rise, and consequently the kinetic energy it possesses, is multiplied ninefold.

84. The law of the *Conservation of Energy* asserts that the quantity of energy in the universe is a constant quantity. No energy can be created, no energy can be destroyed. Energy may be transformed from one form to another. Water or any raised mass may fall and so lose potential energy; but in falling it will either gain kinetic energy or do work by turning a wheel or in some other way. Gunpowder may explode and so lose its potential energy; but the bullet it has propelled and the gun which has recoiled have kinetic energy. Some of the energy of the powder has changed into energy of sound, and some into energy of heat and light. But if the energy of the bullet, and the gun, the energy of the sound, the heat, and the light be all measured, it will be found that their sum will equal the original energy of the powder. In other words, to do work of any kind, energy must be transformed from one form into another; and if any energy is seen to come into existence at one place, that must be due to an equivalent amount of energy having disappeared in another. No energy can disappear in one form without appearing in some other. Hence, wherever we see energy of one form produced, we should always be able to find that it is due to the transformation of energy of some other form.

85. Consider now the case of the raised stones. Because they have weight they will fall if unsupported, and will then do work in some form or other. In other words, by raising the stones against gravity we have given them potential energy. If they are allowed to fall freely, gravity will do work upon them, which will take the form of kinetic energy equivalent to the energy originally spent in raising

them. In the case of the compressed air, the energy spent in compressing takes the form of potential energy, in virtue of which the air can do work in pushing out the piston against external pressure—the work done may be measured as described above. So in the case of the electrified bodies, if B be allowed to pass from β to α, the electrical forces will do work equal to what was done against them in the previous case. Hence, as a slightly different form of expressing what was said above (sects. 76 and 78), if B be removed from α to β by any path, no matter what, and then be allowed to return to α by any path, there is no work done on the whole, for as much work is done against the electrical forces in the first translation as is done by them in the second.

CHAPTER VI.

ELECTRICAL QUANTITY AND DENSITY.

86. We have seen that a conductor may have a charge given to it in virtue of which it will exert a certain influence on other bodies. If this body be placed in contact with another exactly similar conductor, the charge of electricity is shared between them, and the influence exerted by either singly is different from that exerted by the first in the same circumstances. If the original charge is distributed in a similar manner over a number of conductors, the effect due to any one of the charged conductors is different from that exerted by the original one. Hence we see that electricity exerts an influence apparently depending upon its quantity; and from some of the effects of a charge we may obtain a method of measuring its quantity.

87. For instance, bodies charged with electricity exert either a repellent or an attractive force upon other bodies charged or electrified by induction, and therefore the amount of this attraction under given conditions may be made the basis of measuring electric quantity. The force exerted may be measured in several ways. The instrument originally

used was the torsion balance, of which there is a description in sect. 23. For electrical measurements a slight modification is necessary. The air inside is kept dry by a vessel containing sulphuric acid or chloride of calcium. The torsion wire supports at its lower extremity a horizontal rod of shell-lac carrying at one end a gilt pith ball, B, and a counterpoise at the other. In the cover of the balance there is an aperture through which another ball, A, supported by a rigid insulating stem, can be introduced. The centres of the balls, the rod of shell-lac, and the graduated strip of paper, ought to be all in the same horizontal plane. When the two balls are in contact, the shell-lac rod should point to zero on the scale, and the wire should be without torsion, with the index also at zero.

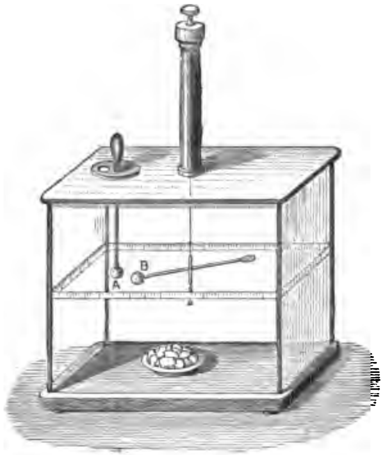


Fig. 42.

88. The instrument being so set, a charge is given to A; it is introduced and touches B, and there is an immediate repulsion. After some oscillations, B comes to rest at an angle α from A. The torsion on the wire is α, and the force of torsion brought into play equals the repulsion between the two balls at a distance $2r \sin. \frac{\alpha}{2}$, where r is the length of the arm carrying B. If the nut be turned through an angle θ tending to diminish the distance between A and B, B will then take up a position β degrees from A, the wire will be twisted through an angle $\theta + \beta$, and the force of torsion will equal the repulsive force between the balls at the

distance $2r \sin. \frac{\beta}{2}$. In this way the force exerted by these spheres at different distances can be measured, and it is found that for any given quantities the force exerted varies inversely as the square of the distance between their centres —that is, if at a distance of a foot the force exerted is represented by the number 1; at six inches, that is, one half of the original distance, it will be 4 times as great; at four inches, 9 times; at three inches, 16; and at two inches, 36. At two feet, that is, twice the original distance, the force will have only one-fourth of its original value. *As the distance is diminished or increased in any ratio, the force is increased or diminished in the square of that ratio.*

89. The next point to be ascertained is, how the force varies with the quantities of electricity on the balls. A and B are discharged, and the apparatus is set as previously described. A is charged and inserted. It touches B, and repulsion ensues. The wire is twisted so as to bring the balls to a certain distance, D, from each other, and the repulsion is measured by the torsion of the wire. By removing A, and making it touch an exactly equal and similar ball, A's remaining charge is halved; and on A being replaced, the force now necessary to keep the balls at the same distance is again measured by the torsion. B's charge is similarly halved, and the force again measured, and so on.

If E and E′ be the original charges on A and B, and T′ the torsion, $\frac{E}{2}$ and E′ and T″ the charges and torsion in the second case, $\frac{E}{2}$ and $\frac{E'}{2}$ and T‴ the charges and torsion in the third case, &c., and D the fixed distance; then it is found, as the result of very careful experiments, that the force exerted at a fixed distance is always proportional to the product of the numbers representing the charges—that is:

$$T' : T'' : T''' :: E \times E' : \frac{E}{2} \times E' : \frac{E}{2} \times \frac{E'}{2} :: 1 : \tfrac{1}{2} : \tfrac{1}{4}$$

Hence if two balls removed beyond the influence of other electrified bodies, and charged with E and E′ units of electricity respectively, are kept at a distance r from each

other, they will exert a force represented by the expression $\frac{EE'}{r^2}$. If the electricities are different, their signs will be, the one +, the other − ; their product will therefore be −, and − signifies an attractive force ; when both are + or −, the product is positive, which indicates repulsion.

The force exerted between two small bodies charged respectively with E and E′ units of electricity, is proportional to the product of the charges divided by the square of the distance.

90. The electrostatic unit of electricity is that quantity of electricity which, when placed at unit distance from an equal quantity, repels it with unit force (when air is the medium between them). The units adopted are the centimetre, gramme, and second. The force exerted by these quantities so placed would generate, if acting for a second on a gramme of matter perfectly free to move, a velocity of one centimetre per second. The equal quantities may be obtained by charging one of two exactly similar conducting balls with electricity, and then placing it in contact with the other ; evidently the charge will be equally divided between the two.

91. Coulomb's experiments with the torsion balance to prove the above laws were carried out with an extraordinary degree of care and accuracy ; but there are several circumstances which render a perfectly accurate result almost impossible except in one or two cases. He pointed out that these laws are rigorously true only when all extraneous conductors have been removed beyond the influence of the electrified bodies. These must be spheres, and separated by distances, large compared with their diameters. When the charges on the repelling spheres are unequal, repulsion ceases at a certain distance, and at all smaller distances there is attraction. His results, so far as they go, have been completely verified by later experimenters ; but the best proof of the truth of his law is derived as a mathematical consequence of the experiment described in sect. 103.

In all these experiments there was an unavoidable loss of electricity by dissipation into the air. The method followed by Coulomb to compensate for this was extremely ingenious, but want of space allows us only to allude to it.

92. When two equal balls are insulated, and a charge is given to one of them, and the second is charged by contact with the first, it is found that the charge is divided equally between the two. Hence if the charge be uniformly distributed over the surface of each, the quantity of electricity per unit of surface of either is half what it was on the first. The electric density of a uniformly charged surface is the quantity of electricity on a unit of area. Where the distribution is not uniform, the electric density is the quotient obtained by dividing the quantity of electricity distributed over a small portion of the surface by the area of this portion. As we increase the surface of a conductor, the charge remaining constant, the density on any one portion diminishes. Thus, when a chain is charged and laid on the plate of an electroscope by means of a glass rod, the gold leaves diverge considerably when the chain lies in a heap on the plate. As it is lifted up, the leaves approach each other, because the surface of the conductor being increased, the electric density on the gold leaves is less, and consequently their repulsion is diminished.

93. *Electricity found only on the outer surface.*—Experiment teaches us that electricity is exhibited only on the surfaces of conductors; this is shewn by the apparatus represented in fig. 43. A brass ball is suspended by a silk thread, and

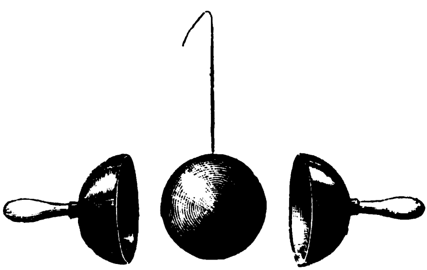


Fig. 43.

covered with two hemispheres of brass, which are held by insulating handles, and exactly fit it. A charge is communicated to the ball so compounded. The hemispheres

are put on so as to inclose the ball entirely, and they are found to be electrified. When they are carefully withdrawn, not the slightest charge is found on the ball. No electricity is found on the inner surfaces of two gold leaves diverging under the same charge.

94. A *proof plane* is an instrument used in measuring the density of electricity upon different parts of the surface of a conductor. It consists of a small circular disc of gold leaf or gilt paper fastened to the end of an insulating stem (A, fig. 44). The disc is small compared with the conductor under investigation, and its thickness is small compared with its radius. It is laid flat upon the part of the surface to be examined, and being thus made to form part of that surface, it acquires a charge proportional to the density of electricity at that part. This charge is measured by means of an electrometer. The proof plane having been discharged, is applied to some other part of the conductor, and the new charge measured as before, and so on in succession to different portions of the surface. The ratio of the measurements with the electrometer is the ratio of the densities at the parts touched.

Fig. 44.

95. That electricity is found only on the outer surface may also be shewn by the following experiment. A hollow spherical metallic conductor of ever so thin material on an insulating stand, with a hole in the top, is charged. A proof plane is made to touch different parts of the outer surface, and when removed is always found to be electrified. But

when the proof plane is tested, after having been made to touch the interior, it is found to possess not the very least charge; proving that none of the charge is in the interior of a hollow conductor. Care must be taken, in removing the proof plane from the interior, that it does not touch, or receive a spark from the edge of the hole.

To Faraday's ingenuity we owe the following experiments illustrating the same fact. A cylinder of wire network (fig. 44), whose meshes need not be fine, is placed upon an insulating stand, and charged either positively or negatively by communicating a charge either to the inside or the outside. When the cylinder is examined by the proof plane, the charge is found on the outer surface only.

Faraday attached a conical bag of cotton gauze to a ring, which was supported on an insulating stand, and kept it distended by a silk thread attached to the apex. It was electrified, and the proof plane shewed that the charge was wholly on the outside; none whatever on the inside. The bag was turned inside out by means of another silk thread and again tested. Considerable charges were again obtained from the outer surface of the bag, but none from the inner—the electricity having changed from the one surface to the other.

96. Faraday made experiments to ascertain what effects a charge given to a conductor exerted throughout its interior. In one of these he had a large cube whose sides were of thin metal. This was carefully insulated, and then submitted to violent discharges from a powerful electric machine. In the interior of the cube, which was full of air, were several very delicate electroscopes; but at no time before, during, or after a discharge, could he detect the slightest trace of electrification on them.

One very useful application of this is when it is desirable to keep any electrical apparatus free from the inductive action of other electrified bodies. The apparatus only requires to be surrounded by a screen of conducting material. It may be continuous, or it may be simply coarse wire-netting. Such a screen effectually prevents any inductive action.

97. The next point to be noticed is how a charge given to a conductor is distributed over its outer surface. We may consider first the cases where the conductor is uninfluenced by other conductors. Coulomb found, by the aid of a proof plane and the torsion balance, that the density on different parts of a conductor depends upon its shape. Investigations based upon the mathematical theory of electricity have in many cases shewn what the distribution should be; and in every case which has been solved, theoretical deductions have entirely agreed with the experimental results.

In the case of a sphere, the density is the same at every point of its surface. In an ellipsoid formed by the revolution of an ellipse about one of its axes, the densities at the extremities of the two axes are proportional to the axes—consequently there is a greater accumulation at the extremity of the major axis; or more generally, the density at any point is proportional to the perpendicular from the centre upon the tangent plane at that point. Hence the difference in the electric densities on the ends and sides of a conductor gets greater and greater as the conductor is more and more drawn out in shape. Theoretical investigations shew that on a cone

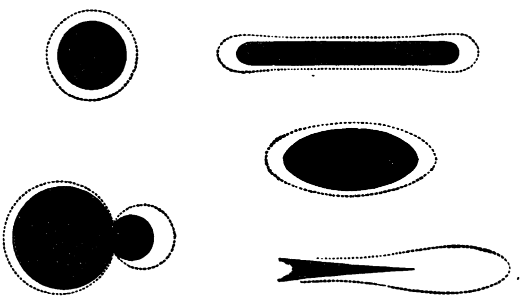


Fig. 45.

the electric density should be infinite at the apex, and in practice it is found impossible to keep a permanent charge on a pointed body; the charge is gradually given off to the air surrounding the point. The variations in electric density at

different parts of a conductor will be best understood by reference to the figures. It is to be observed that the distance of the dotted line from the surface is intended to represent the relative electric density at the different parts, but it must not be supposed that there is actually a layer of electricity on the body of the depth indicated. When the dotted line is inside the body, a negative electrification is indicated.

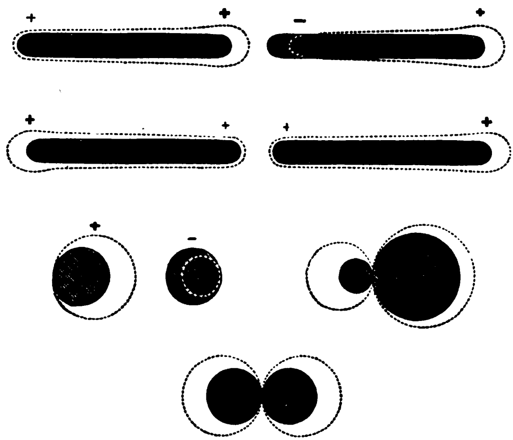


Fig. 46.

When other bodies, charged or not charged, are near, the distribution of electricity on the conductor is greatly affected. The phenomena will be best understood by referring to the figures.

In such cases the distribution is said to be affected by Induction.

CHAPTER VII.

INDUCTION.

98. We have already shewn in sect. 54 that a body originally non-electrified can be charged without being in contact with another charged body, or by any of the other processes mentioned in sects. 61, 62. We shall now consider the phenomenon more fully.

99. When a body charged with electricity, as the insulated brass ball A, is brought near a brass cylinder B, with rounded ends, uncharged and mounted on an insulating stand, it is found that the cylinder shews signs of being electrified—the end nearest the ball having the opposite kind of electricity,

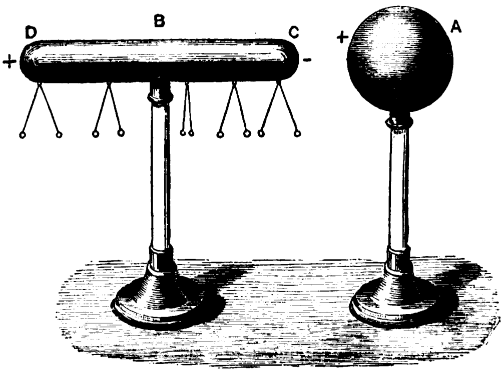


Fig. 47.

while the end farthest away has the same kind as the ball. It is then said to have a charge induced upon it by A. If the cylinder has previously been provided with pairs of pith balls hung by cotton threads at different parts of its length, the balls of each pair will by conduction be charged in the same way as the portion of the cylinder to which they are attached, and will consequently repel one another, as shewn. The amount of this divergence varies with the distance of A

from B, being greatest when the distance is least, and diminishing as A is removed, until at last no sign of electrification can be found—the electrification is manifest only during the proximity of A. Moreover, for a given distance of A from B, the angle between the balls differs with their position on the cylinder; being greatest when they hang at the extremities, and zero near the middle. This agrees with what is established by a proof plane and an electrometer, that the density of the electricity is greatest at the ends, and diminishes as we recede from them; being zero at a line nearly coincident with the middle. The position of this line varies with the proximity of A to B; but is always between the middle of B and A, and shifts nearer to the end as A is brought nearer.

It can easily be demonstrated by a proof plane and an electroscope that the end of B nearest A is always charged with the opposite electricity to that of A, and the end farthest from A is charged with the like electricity. Thus, if A be charged positively, there will be negative electrification at C and positive at D (fig. 47). If A be negative, C will be positive and D negative. That the induced electricities are equal in amount, is

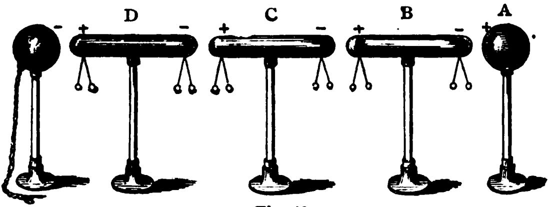


Fig. 48.

proved by the fact that they neutralise each other when the ball is withdrawn. If the cylinder were made up of two parts, each supported by a glass stem, it would be found, on separating the two in presence of the charged body, that the one end was electrified positively and the other negatively. The action of the electricity of the charged ball inducing in the cylinder this peculiar electrical condition is called *induction*, and the cylinder in this state is said to be *polarised*—that is, its ends have similar and opposite properties.

100. The electricity induced on either end of the cylinder behaves in many respects as if it were a free charge. This can be shewn by its action on other bodies. If another cylinder, C, is placed near the first, as in fig. 48, it is found, on the approach of A to B, to be affected by B in the same way as B was by A; and to have the power of similarly influencing another cylinder, D. The series may be continued indefinitely with the same results. When the charged ball is withdrawn, the whole series returns to its natural condition without being in any way permanently affected. The moment A is again brought near, each cylinder becomes again polarised, and there is manifested at the farther end of the last, a charge of positive electricity, which exerts the same influence on other bodies as if a portion of the electricity of the ball had been actually communicated or transferred to it. But the induction does not stop here. It is found that there is a charge induced, on the furniture and walls of the room, the clothes of the experimenter, &c., equal and opposite to the original charge.

101. If while A is close to B (fig. 47), we touch any part of B with the finger for an instant, the pith balls at D collapse, and those at C diverge rather more. If A be then removed, the pith balls will again be seen to diverge, and it will be found on testing with a proof plane that B has a permanent charge of negative electricity. The explanation is, that the proximity of A charged, separates the neutral electricity on B, drawing the unlike kind towards the extremity nearest it, and repelling like electricity to the other extremity. On B being put in connection with the earth, the repelled positive electricity runs to the ground, the negative electricity is retained, and on A being removed, spreads over the whole of B. If an insulated conductor in the neighbourhood of a charged body is put in connection with the earth for an instant and then removed, it is found to have a charge of the opposite kind of electricity.

102. We are now in a position to understand how a charged conductor attracts light bodies and repels them after contact. Let A (fig. 49) be a conductor charged positively. By induction it separates the neutral electricity of B, drawing negative

electricity to the nearest side, and repelling positive to the farther side. By the law of attraction (sect. 88), the negative electricity being nearer A, is attracted with a greater force than the positive is repelled, and consequently B as a whole is attracted. Similarly with the gold leaves of the electroscope. When they are charged they induce an opposite charge chiefly on the tinfoil pasted on the interior of the glass cover. There is attraction between the oppositely electrified surfaces until contact takes place; when the electricities neutralise one another, and the leaves fall back.

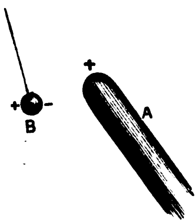


Fig. 49.

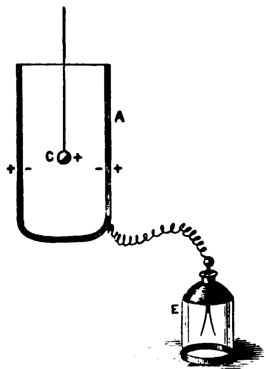


Fig. 50.

103. *The amount of the opposite kind of electricity induced by an electrified body on surrounding conductors is equal to that of the inducting body.* It was Faraday who proved this by the following experiment. He insulated an ice pail, A (fig. 50), ten and a half inches high and seven inches in diameter, and connected it by a wire with the knob of a gold-leaf electroscope, E. A brass ball, C, suspended by a long dry thread of white silk, was charged with positive electricity, and introduced within the pail. By induction the electricity on the pail was separated, negative electricity being on the inner, and positive on the outer surface, the wire, and the electroscope. When the ball was removed, the

electrification of the inner and outer surfaces of the pail and of the wire and electroscope disappeared. On C being again introduced, the same separation took place; the divergence of the leaves caused by the induced positive electricity increasing as the ball was lowered, until it had sunk three inches below the opening, below which they remained steadily in the same position at whatever depth it was, and whether it was near or far from the sides. This shews that at depths of three inches and more the charge induced by C is at the maximum, and that at such depths the ball is practically wholly inclosed by the pail. The ball was lowered till it touched the bottom, and communicated its charge to the pail, the leaves still remaining in the same state as before. The ball when lifted out was found to be entirely uncharged; shewing that the positive electricity developed by induction on the outer surface was exactly the same in amount as that of the ball itself. The negative electricity of the inside of the pail, being equal to the positive on the outside, was therefore equal to the positive electricity of the ball, but opposite in kind. Faraday varied the experiment so as to have four insulated pails inside one another, and the effect on the outmost pail was exactly the same as before. Nor was any difference found on substituting a similar vessel of any other substance for the inner pail. We may conclude from this and similar experiments that, on the walls of a room, or other conductors surrounding a charged body, the total amount of the opposite electricity induced is equal in amount to that of the body itself.

As this is very important, we give another illustration. If we imagine a conductor charged positively, say, and which we may for definiteness suppose spherical, surrounded by any number of other spherical conductors, all insulated from it and from one another: we shall always find on the external surface of the outer one a positive charge equal in amount to the charge on the conductor, and the electrical effects at external points will be the same as if the original conductor had alone been present, independent of the radius of the outer one or of the number of those inclosed within it. If the outermost conductor be connected with the earth, then

no effect due to it will be experienced at points external to it, and no charge will be found upon its outer surface; but a charge equal and opposite to the original charge will remain on its inner surface.

104. By similar experiments it can be established that, if conductors charged with the same or opposite electricities be placed as above in the interior of a hollow metal globe or pail, their inductive action will develop on its outer surface a charge equal to the algebraic sum of all their charges. By using such a vessel and an electroscope, it can be shewn that when any two substances are rubbed together, equal quantities of the opposite electricities are produced. Let each of the two substances be insulated and then rubbed together. On introducing either into the pail the gold leaves will diverge—in the one case with positive electricity, in the other with negative. But if we put both into the pail together, still insulated and not touching, there will not be any divergence of the leaves; shewing that the quantity of electricity is the same on each.

It is mainly from induction that the difficulty arises of measuring exactly the attraction which two known amounts e and e_1 of electricity on two conductors A and B exert upon each other at a given distance, as in the torsion balance. The e on A induces a quantity e' of negative electricity on B—the amount of which is not easily ascertained except when the bodies are spherical; e_1 also induces e_1' on A; these induced charges e' and e_1' respectively induce fresh amounts of electricity, and this is continued in an infinite series. The apparent attraction therefore is not due to the original quantities by themselves, but to them modified by the inductive action. The amount of the induced charge, and the distribution of the original and the induced charges, vary with the distance between the bodies, the configuration of the bodies, their shape, the presence of other bodies, and the dielectric.

105. By an exhaustive series of experiments, Faraday investigated the phenomena of induction as depending upon the insulating medium or dielectric between a charged body and those affected by it.

A rod of shell-lac, A (fig. 51), is surmounted with a hemispherical metal ball, B. A is charged negatively by rubbing

it with flannel, and the neutral electricity on B is separated; on connecting B for an instant with the ground, a positive charge is left on it. Faraday placed a proof plane successively in the positions *a b c d e f g h i*, touched it, and then removed it to an electroscope, and found that in every case it was charged positively; charged, therefore, by the inductive action of the wax. But the amount of the induced charge varied; the amounts being in the order *c d h i g e f*, *c* giving more than three times the charge that *f* gave. This proves that the inductive action must radiate from the inducing body, not merely in straight lines, as was formerly supposed, but also in curves. The same results were found when other gases were substituted for air.

Fig. 51.

106. By other experiments, in which Faraday interposed various dielectrics, both liquid and solid, between the inducing body and the proof plane, he established that in every substance the lines of induction are curves. When, however, a hollow metal cylinder, in connection with the ground, surrounded A, so as to interpose between A and the proof plane, the latter shewed no charge wherever it was placed, until the cylinder was removed, when the usual charge was found on it.

107. Faraday next, by a variety of experiments, proved that the quantity of electricity induced by a charged conductor upon the surface of another conductor depends not only upon their distance asunder, but also on the particular medium. A, B, and C (fig. 52) are metal plates. C is insulated, and A, B, at equal distances from C (I.), are each in electric communication with one of the gold leaves, *a*, *b*, but also insulated. The distance of A or B from C can be varied at pleasure. C is charged positively, and A and B are touched simultaneously for an instant. They are then found to have a negative charge, but the leaves remain vertical. A is then placed nearer C (II.) without the insulation being disturbed, and immediately the leaves attract; the nearer surface of A is found on examination to be negatively electrified; the outer surface of A, the wire, and *a* are positive;

while the outer surface of B, its wire, and *b* are found negative. For on the nearer approach of A to C some of the neutral electricity in A is separated, the negative portion

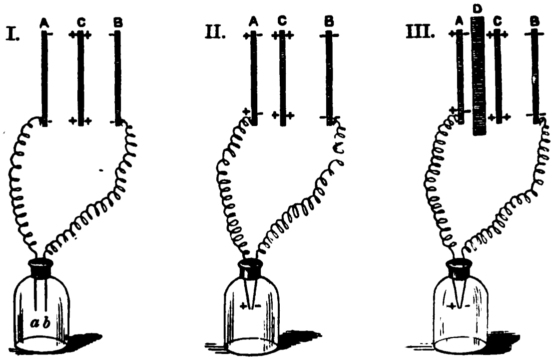


Fig. 52.

being drawn near C, the positive spreading over the outer surface of A and *a*. At the same time part of the negative electricity on B, previously kept there by the inductive action of C, is set free, and reaches *b*.

108. A, B, and C being placed and charged as at first (III.), the same result followed the introduction of a cake of shell-lac between A and C, as was obtained when A was moved nearer to C than B was. This shews that the inductive action of C on A is greater when the interposed medium is partly shell-lac and partly air than when it is air alone—that is, the induced charge is greater when the medium is shell-lac than when it is air, other conditions remaining the same. Similar results were obtained by substituting discs of glass, sulphur, &c. for the shell-lac. Faraday used the term specific inductive capacity to denote the power of a dielectric to transmit induction, as compared with that of air. He found that all gases have the same specific inductive capacity as air, whatever be their temperature or pressure, and that every other substance he tried had a greater specific inductive capacity than air. It has been

recently shewn, however, that the specific inductive capacities of all gases are not the same.

109. The question Faraday next attempted to solve was of this nature. In sect. 99 it is shewn that a body charged with electricity exerts an influence on other bodies at some distance from it. Faraday had discovered (sect. 108) that the amount of electricity induced depends on the dielectric or insulating medium interposed between the charged body and those acted on. He surmised from this that the induction must be due to some action in the medium, which will vary with the particular medium employed. A similar phenomenon occurs in acoustics. A sound was produced under the surface of the Lake of Geneva, and was propagated both through the water and the air. It took a shorter time to travel a given distance through water than through air. This is easily explained when we know that the propagation of sound consists in the transmission of a particular kind of disturbance through the medium, and the rate of transmission varies with the properties of the medium in question. Or as in the case of a bell rung at some distance off by the aid of a wire: the action at a distance can be explained when we know that there is a similar handing on of a pull, and consequent motion of the successive parts of the wire, till it reaches the mechanism which causes the bell to sound. Previous to Faraday's researches, it was known that the one body exerted an influence on the other, but it does not seem to have occurred to any one to inquire whether it was due to the action of the medium or not. What Faraday sought to find was, what is the nature of the action in the medium, and what properties of the medium will account for it?

110. His theory is as follows: When any substance is in presence of an electrified body, every one of its particles becomes polarised—that is, acquires equal and opposite properties on opposite sides—which we may suppose due to the separation of the neutral electricity in it, the opposite electricity to that of the body being on the side of the particle next it, an equal amount of the like electricity on the farther side. This state of polarisation is first produced in the layer of particles nearest the charged body; the first layer then

induces a similar condition in the next one, and in this way the polarisation is propagated throughout all space. Hence two adjacent particles have oppositely charged ends next one another. The particles when polarised resemble a number of magnets or iron filings in the presence of a magnet, or the cylinders of sect. 100. The amount of the displacement of electricity, or the separation of the neutral electricity, in the particles of any one medium is proportional to the electro-motive force* to which it is exposed—a greater electro-motive force producing a greater displacement. In different media subjected to equal electro-motive forces, with other conditions the same, the displacement varies, depending upon a property of the medium which Clerk Maxwell has named electric elasticity. This property of electric elasticity is analogous to the elasticity of an elastic substance, and to the coercive force of steel. Just as with two elastic bands perfectly similar as regards length, cross section, &c., or two spiral springs, the same appended weight may produce twice the extension in one that it does in the other, so the same electro-motive force may produce in the particles of one of two media double the electric displacement that under exactly the same conditions it produces in the other. The electric elasticity has also the property of causing the medium to recover its original condition when the electro-motive force is removed, just as the elasticity of the elastic band enables it to recover its original length and form when the appended weight is removed. The displacement under given circumstances in air would be only half what it is in shell-lac. Hence the coefficient of electric elasticity is twice in air what it is in shell-lac. It is due to this electric elasticity that the displacement disappears when the electro-motive force is removed. In this theory all substances may be considered as consisting of conducting particles immersed in an insulating medium, and so insulated from one another to a greater or less extent. The displacement is limited by the insulating power of the medium. In a non-conducting

* Whenever there is a tendency to a passage of electricity from one point to another, there is said to be an electro-motive force between them. (We shall see later on to what this tendency is really due.)

substance the particles may be polarised to a considerable extent before two contiguous particles will discharge into one another. In a conductor the insulating power is so small that these discharges take place with great ease, and so the polarisation disappears as quickly as it is produced. At any point in the interior of a conductor the opposite electrifications of contiguous particles neutralise; but at the surface there will be an apparent superficial electrification, constituting what on the old theory is called the electrification of the conductor. In other words, 'it is only at the surface of the dielectric that the effects of the electrification become apparent, although the polarisation exists throughout the whole of the interior, but is there neutralised by the juxtaposition of neighbouring parts.' A somewhat analogous phenomenon is seen in the surface tension of liquids. That is mainly due to forces exerted between the particles of the liquid, but the effects are apparent only at a surface, that is, only where there is a break in the continuity.

111. By this theory the energy of an electric charge consists in the polarised condition of the dielectric. In a conductor the state of constraint is continually giving way, the potential energy of the state of constraint being transformed into heat. When a continual flow or current of electricity takes place, it is due to the electro-motive force continually re-establishing the state of constraint as soon as it is destroyed.

The dynamical part of the theory requires that at every point in the medium there must be a tension in the direction of the resultant force R at that point, and a pressure equal to the tension in every direction perpendicular to R. By supposing these to exist, their mechanical effect on any portion of the medium bounded by any surface is identical with the mechanical effect of the electrical forces, according to the ordinary theory of action at a distance; besides agreeing with the form taken by the lines of force.

The theory gives a satisfactory explanation of the fact that equal quantities of electricity are always produced simultaneously—that no absolute charge can be given to matter. The difference between conductors and insulators as above

noted, consists in the capability of sustaining the forced condition of polarisation or of readily allowing this to decay. It also follows as a consequence that the amount of electricity induced is always equal to the charge.

It also follows as a consequence of this theory that no induction can take place between two conductors at the same potential, and that the amount of induced charge is proportional to the difference of potential between the induced body and the body inducing.

CHAPTER VIII.

POTENTIAL.

112. In sect. 76 one method is given by which the work done in transferring a portion of attracted or repelled matter from one position to another may be estimated: there is another which is of great importance, especially in gravitation, magnetic, and electric problems—namely, in terms of the difference of potentials at the original and final positions.

113. The potential at a point due to electrical or magnetic attraction is the work required to carry away a unit of negative electricity, or of south magnetism, from the point to an infinite distance against the electric or magnetic attraction. Suppose that at a certain point α (fig. 53) we have a particle charged with a quantity of negative electricity, and that there are other electrified bodies, A, B, C, &c. in the neighbourhood. They will exert an attraction on the particle. To remove it from them will require work to be done against the electric attraction, and also perhaps against magnetic and gravitation attraction, and friction; these latter we are not at present concerned with. As the particle is removed farther and farther, the attraction at any position will in all likelihood diminish, and the work to remove it

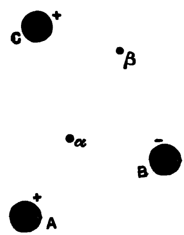


Fig. 53.

a given space farther will also diminish; and both will vanish when the particle is very far removed from the attracting bodies. Let the charge on the ball be a unit of negative electricity, and let the whole work spent in overcoming the attraction of A, B, C, &c. from α to an indefinitely great distance be V_α. V_α is called the potential at α. To take the same particle from β to the earth would probably require a different amount of work $V\beta$, and the potential at β is then said to be V_β. In bringing a particle charged with a unit from an indefinitely great distance to α, an amount of work would be done by the electrical forces equal to what was spent against them in going from α to a great distance.

114. It is found as an immediate consequence of the fact that a body is completely discharged when made to touch the interior of a hollow and virtually closed conductor (sect. 103), and also as an experimental fact (sect. 88), that if E be the number of units of electricity on one body, e the quantity on another, and r be the distance between them, the force exerted by the one on the other is represented by the formula $\frac{Ee}{r^2}$. The same law also holds for gravitation and magnetic attraction, and therefore all theorems derived from this law for gravitating matter hold also for similarly electrified or magnetised bodies.

In considering the application of these theorems and definitions to electrical phenomena, we must observe that because of the dual nature of electricity the same amount of work may be done either by removing a given quantity of negative electricity from α to β, or by bringing up an equal quantity of positive electricity from β to α.

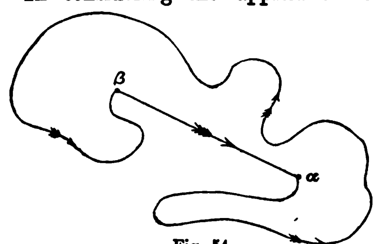


Fig. 54.

115. The following theorems are among the most important. Geometrical proofs of them will be found in Thomson

and Tait's *Elements of Natural Philosophy*, sects. 479 and 488; to which book we would strongly recommend every one to apply who wishes clear statements upon this and almost every other dynamical question.

116. (I.) If the different points of a spherical surface attract equally, with forces varying inversely as the squares of the distances, a particle placed within the surface is not attracted in any direction.

(II.) The attraction of a spherical shell on an external particle is the same as if the whole mass were collected at the centre.

Thus, if there be a spherical conductor A (fig. 55) charged with a quantity E of positive electricity, a negatively charged particle placed anywhere in the interior, say, at α, will experience no attraction whatever—that is, there will be no tendency for it to move in any one direction in the sphere. A negatively charged particle outside, at β or at γ, say, will be attracted with a force

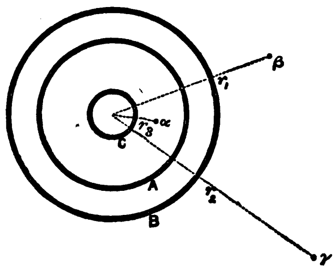


Fig. 55.

directly proportional to the charge, and inversely as the square of the distance from the centre. The attraction of A on the particle at β, if charged with a unit of negative electricity, would be $\frac{E}{r_1^2}$; of A on the same quantity at γ would be $\frac{E}{r_2^2}$; on the same quantity at $\alpha = 0$. Hence, the same charge given in succession to spheres of different radii will always exert the same attraction on the same charge at external points, so long as it keeps the same distance from the centre of the charged sphere.

Thus, if we remove the shell A, and replace it by either of the shells B or C—their centres lying where A's was, and charged with the same quantity E—although the density

(sect. 92) is different from what it was on A, the attraction on one unit at β and at γ will still be $\frac{E}{r_1^2}$ and $\frac{E}{r_2^2}$ respectively. The attraction of the charged shell B on a unit at α will still be 0; in C's case, as α is external to C, the attraction is $\frac{E}{r_3^2}$.

117. It can be shewn by a mathematical investigation too advanced for this work, that if there is a quantity Q of electricity concentrated at a point, the potential due to it at a distance r is $\frac{Q}{r}$, which is + or −, according as Q is positive or negative. It can also be shewn that if there are several quantities Q_1 Q_2 Q_3 &c., condensed in points at distances r_1 r_2 r_3 &c., from a given point α, the potential due to them at α is $\frac{Q_1}{r_1} + \frac{Q_2}{r_2} + \frac{Q_3}{r_3} +$ &c., or $\Sigma \frac{Q}{r}$, where Σ is used to signify that all these quotients are added together: effect being given to any of the charges being negative.

The potential due to a given distribution of electricity has in general different values at different points. It may be positive at some points, negative at others.

118. Suppose that the value of the potential for one point a is V_a, and for another b is V_b, then the work required to carry unit of negative electricity from a to b is $V_a - V_b$. Because, as the path pursued in going from the one position to the other does not affect the amount of work done (sects. 76, 78, 85) against the electric forces, we may suppose the change of position to be effected by going from a to infinity, and then from infinity to b.

119. If F be the average value of the attraction between a and b, then $F \times ab = V_a - V_b$, since each expresses the work done in transferring a unit from a to b: therefore $F = \frac{V_a - V_b}{ab}$; that is, the average value of the attraction upon a unit, or the average value of the force tending to move a unit in any direction, is the rate at which the potential falls off per unit of length in that direction. When a and b are very near, the average coincides with the actual.

Hence the force exerted on unit mass or quantity of electricity in any direction is the rate at which the potential falls off in that direction. In the case of gravitation, the potential has different values at different heights above the earth's surface; and what we call the acceleration due to gravity, is equal to the rate at which the potential falls off in the vertical direction. If the potential is the same at *a* and *b*, two points near one another, there will be no work done in moving a unit from one to the other; hence the resultant force will be zero there. Conversely, where the resultant force is zero, the potential is constant.

120. An *equipotential surface* is one at all points of which the potential has the same value. In the case of an equipotential surface, the attraction or the resultant force is everywhere perpendicular to the surface. Because (fig. 56) if the attraction, F, were inclined at an angle α to the normal, it would have a component parallel to the surface equal to F sin. α (sect. 75); that is, the resultant force along the surface would not be zero; in other words, the potential would not be constant.

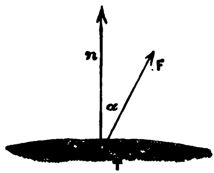


Fig. 56.

Hence equipotential surfaces are surfaces of equilibrium—that is, a particle on such a surface is in equilibrium, so far as the forces under investigation are concerned, since there is no force tending to make it move along the surface. Horizontal or level surfaces are familiar instances of equipotential surfaces with gravitation as the attracting force. What is true of equipotential surfaces in general, is true of level surfaces. The value of gravity is the same at all points at the same level. For instance, no work is done against gravity in passing from one point to another of the same level surface, and the direction in which gravity changes most rapidly is perpendicular to the horizontal. An attracting mass is virtually inclosed in a series of equipotential surfaces which may be imagined existing at such distances from one another that the difference of potential between any two successive ones is always the same. In the case of the earth, such a series

would be very nearly concentric spheres at rapidly increasing distances from each other. A particle could be moved from any one part of any one of them to any other part without work being done, and the work in moving it from one position to another would depend solely on the number of such surfaces cut, supposing no surface cut oftener than once.

121. *A line of force* is a line drawn so that the tangent, at every point of its length, is the direction of the attraction at that point. The force at every point falls off most rapidly in the direction of the line of force passing through it. They cut equipotential surfaces at right angles. A particle free to move will always move along a line of force.

Faraday's idea was that from every electrified body lines of force or induction, as they are also named, may be supposed to proceed in all directions to all space, and that the number issuing from any body depends upon and is a measure of the quantity of electricity in it. Wherever any of these lines terminate, on the earth, the sun, the walls or floor or roof of a room, or other bodies, there is an equal and opposite quantity of electricity to that on the part from which they proceeded. Lines of force can be found by one method or another, and from them we can ascertain what are the forms of the surfaces of equilibrium round a conductor, what is the surface density of electricity at different points on variously shaped bodies, where on a given conductor the density would be greatest, where least; or the surfaces of equilibrium may be found, and from them we can deduce the lines of force.

122. To illustrate the properties of potential further, we introduce some analogies. By comparing the value of the potential at a point with the values in the neighbourhood, we ascertain whether and in what direction an electrified particle placed at the point will move. A particle of attracted matter free to move always moves from places of higher to places of lower potential; that is, in the direction in which its potential energy diminishes. In the case of gravitating matter, height above the sea-level corresponds to rise of potential, and hence a stone *falls*—water invariably flows from places of higher to places of lower level. In thermal questions, temperature is closely analogous in many respects to potential in electricity:

and we find that heat invariably flows from the body of higher to the one of lower temperature. In fluids, again, the flow is always in that direction in which the pressure falls off most rapidly. Consequently, if it is known where the barometer is high, and in what direction it is falling off, we expect a strong wind from the places where the barometer is high to those where it is less. So when the pole of a magnet is brought into the neighbourhood of iron filings, the filings move towards it, because in so doing they are moving so as to diminish their potential. Just as in all these cases the direction of motion is from places of higher to places of lower level temperature or pressure, so in electricity the flow is always from points of higher potential to those of lower, and always in the direction in which the potential falls off most rapidly, which is not in general a straight line.

123. Just as one point is said to be at a higher level than another, although no stone or water may be there, so in electricity, two points may be at different potentials, although there is no charge at the points.

As has been stated, the flow of water is in many respects closely analogous to the assumed flow of electricity, and by studying the phenomena of the one we may learn something about the other. If there be two cisterns of water at different levels, there will always be a tendency for water to flow from the one at the higher level to the other. So long as the *difference of level* is the same, it is immaterial to the amount of flow whether the two cisterns are both above the level of high water, or one above and one below, or both below. So again in heat conduction, the rate at which the heat passes from one point to another at a different temperature is simply proportional to the *difference of temperature,* whatever be the temperatures, if we suppose other properties involved to remain constant. Similarly with electrical phenomena. A conductor, A, charged with + E, is said to be electrified positively. By that is meant that + E would flow from it to the earth, if they were electrically connected. It may have negative potential relatively to some other conductor, B, which is charged positively, but to a higher potential than A. So a conductor, C, with negative electrification, has negative

potential relative to the earth and to all other conductors charged positively, and to a conductor charged to a smaller negative potential, but it has a positive potential to conductors at a higher negative potential.

124. The earth is so large and so good a conductor that its electrification remains practically constant. No electricity that we can take from it or give to it alters its electrification or its potential to any appreciable extent. Hence it is used as the body with which all others are electrically compared, and its potential is taken as *zero potential.* The work required to carry an electrified particle to the earth is the same as to an indefinitely great distance or to infinity, and the phrase 'put to earth' is used to signify that the conductor spoken of is discharged or reduced to zero potential. All points at which the potential is greater than that of the earth have *positive potential:* all points at which the potential is less have *negative potential.* A positively charged particle placed at the point of higher potential, would tend to move to the other, and if there were charges at the points and electrical connection was made, positive electricity would flow in the same direction till equality of potential was established. (This is the conventional way of describing the phenomenon; but at present it is not known whether the equilibrium is produced by a flow of positive electricity in one direction, or by a flow of negative electricity in the other, or by a simultaneous flow of both electricities in the two directions.) Of two points at both of which the potential is positive but of different values, the less has negative potential relative to the greater; and similarly, for two negative points, the one for which $\Sigma \frac{Q}{R}$ has the smaller numerical value, has positive potential relatively to the other.

125. The *Electromotive Force* is the name given to the tendency of electricity to flow from one conductor or one point to another conductor or another point, and depends upon the difference of potential between them.

126. A flow of electricity between two points is due to their being at different potentials. An absence of flow between places electrically connected, or an absence of

disposition of a charged particle to move from one to the other, indicates that they are at the same potential. One invariable effect of a flow or current of electricity is to generate heat. *The potential is constant over a charged conductor*, otherwise there would be a constant current between points at different potentials. This means a creation of energy without an equivalent supply; by the conservation of energy this is impossible. No work is necessary to move a charged particle from one part of a conductor to another. The potential is constant over an insulated conductor, even when the electrification varies from point to point, as when some parts of the conductor are +, others −, and one part has no electrification at all. This happens when an uncharged insulated conductor is in the field of a charged conductor. That it must have the same potential throughout is manifest when we consider that, were it not so, there would of necessity be a flow of electricity which would produce equality of potential. But we know that the distribution of electricity on its surface does not change. The potential of the conductor is that of its neutral zone.

Clerk-Maxwell proves this proposition in the following instructive way: Starting with a conductor, charged positively at one end, and negatively at the other, he shews that it can be at constant potential if another electrified body is in the neighbourhood. Allow a + particle from a + part of the surface to move from it always along a line of force. It will ultimately either come to a negatively electrified body or go off to infinity. This latter event can happen only in the case of the conductor having a positive potential. Similarly, a − point from the − portion of the conductor passing along a line of force must come either to a positively electrified body or go off to infinity, and the latter case can only happen when the potential of the conductor is negative. Hence, as the potential is supposed constant, the two second events cannot both happen. Hence there must be another electrified body in the neighbourhood.

127. The potential has the same value throughout the substance of a conductor as on the conductor itself. This may also be proved by an appeal to the Conservation of Energy.

128. When a charge of electricity, however small, has been given to a conductor, the communication of more of the like kind is opposed by the charge already given, and work has to be expended to overcome this resistance. The work needed to put in an additional unit of electricity to the conductor is the potential of the conductor. The potential evidently increases with the charge.

129. A conductor or a point is at unit potential when, to put in or bring up an additional unit of electricity, unit of work has to be done.

130. We have seen that electricity distributed uniformly over a sphere acts upon all external bodies as if condensed at the centre, and that the potential at a point at a distance R from a given quantity Q of electricity is $\frac{Q}{R}$. Hence this is the potential of a point on the surface of a sphere of radius R charged with a quantity Q. By sect. 127 this is the value of the potential throughout the interior of the sphere. From this it follows that the capacity of a spherical conductor, or the quantity of electricity necessary to change its potential by unity, is measured by its radius. In simple conductors of similar form, the capacity is proportional to the linear dimensions. If charges of electricity in the ratio of 1, 2, 3, &c. be given to spheres whose radii, or to similar conductors whose linear dimensions, are in the ratio 1, 2, 3, &c., the potential of each would be the same. This might be tested by placing the conductors at such a distance from each other that they exerted no sensible inductive action, and then connecting them by fine wires. If they were all at the same potential, there would be no flow of electricity along the wires.

131. We have pointed out that the potential of the conductor, or the work required to bring up an additional unit to it, is proportional to the charge already in—that is, the potential grows uniformly with the charge. We may suppose the charge to be given by successive instalments of a unit each. The total work in charging will therefore be equal to the number of units put in, multiplied by the average work to put in one, that is, the average potential. As the potential

grows uniformly, the average potential will be the potential when half full. Let C be the capacity of the conductor, Q the number of units of charge. The average potential $= \frac{Q}{2C}$. The energy $= \frac{Q}{2C} \times Q = \frac{1}{2}\frac{Q^2}{C}$.

132. The same charge given to different conductors will produce different potentials. Thus n units given to spheres of radii in the ratio of 1, 2, 3, will have potentials in the ratio of 3, 2, 1. And the energy of the charge will be in the ratio of 3, 2, 1—that is, the same charge given to a small sphere will produce a greater effect than when on a large one. The explanation is, that it requires a greater expenditure of energy to charge a small sphere than a large one, with equal amounts of electricity.

This is again seen if we divide a charge between two equal spheres. Thus n units given to a sphere of capacity C, has energy $= \frac{1}{2}\frac{n^2}{C}$. But if the charge be shared with another sphere of exactly the same size, each will have $\frac{n}{2}$ units, and the energy of both will be $\frac{1}{2C}\left(\frac{n}{2}\right)^2 + \frac{1}{2C}\left(\frac{n}{2}\right)^2 = \frac{1}{2C}\frac{n^2}{2}$ —that is, only one half of what it was before. The loss of energy is accounted for by the energy of the spark which occurred when the two were brought into contact. This is one way of explaining how the energy of a charge on a conductor disappears when it is put in connection with the ground. Because the charge being spread over an infinitely large surface, has its potential thereby reduced to zero.

133. If we have a machine which can produce a difference of potential V, then the amounts of electricity which it can pump into different conductors will depend solely on their capacities, and the energy to be obtained from a conductor charged to this potential will be proportional also to the capacity.

Suppose now that we charge a given conductor of capacity C, with different machines, which can produce potentials V_1

V_2 V_3 &c. Since $C = \frac{n}{V}$, n will be proportional to V. The energy will consequently be proportional to the square of the potential the machine can give, that is, $E = \frac{nV}{2} = \frac{V^2C}{2}$.

134. Again, on a conductor of non-spherical form the electricity accumulates at prominent parts, although the potential is the same all over. Hence the potential energy, which is proportional to $\frac{1}{2}nV$, will be greater and greater according as the accumulation is greater; on a pointed conductor, although the potential is the same on every part of its surface, the electric density is enormous at the point—that is, the quantity of electricity is much greater there, and hence the resultant force is much greater there than at other parts of the same conductor.

135. There are many ways in which a difference of potential may be produced. One is the contact of dissimilar bodies. Thus, when the glass rod and the silk are put in contact and separated, the glass is found charged with + E, the silk with —. Moreover, with any two substances, the difference of potential produced by contact is constant. Thus in an electrical machine all that is done is to produce a certain difference of potential between the prime and secondary conductors (sects. 138, 139). If the secondary conductor be connected with the earth, and therefore at zero potential, the potential of the prime conductor is the difference of potential which the machine can produce. If the prime conductor be connected with the ground, then the negative or secondary conductor will have a negative potential equal numerically to the difference of potentials the machine can give. In this way an electric machine strongly resembles a pump. All that a pump can do is to raise water say from one level to another. It can change the level of the water by a certain maximum amount. If this be 30 feet, then the pump can raise water from a depth of 30 feet to the surface of the ground, or from 10 feet below the ground to 20 feet above it, or from 50 feet above it to 80 feet above it. The absolute level makes no difference in regard to its lifting power. In the case of an electrical machine, all that the machine does is to produce a given

difference of potential. If the one conductor be kept at a constant potential B, the machine will always tend to keep the other at another constant potential A, so that A - B is constant. Although the difference of potential between the conductors of a machine remains always the same, what may be termed its productiveness is very materially affected by the absolute values of the potential of the negative and prime conductors. For instance, suppose that the machine is driven at the same rate (1) when the negative conductor is not connected with the ground; (2) when it is. The machine will tend to maintain in each case the same constant difference of potential. Suppose while the machine is kept steadily working, a conductor D, uncharged and therefore at zero potential, is held to the prime conductor. In (1) the potential of the prime conductor will be V, and of the negative conductor V^1, where V^1 will be as far below the potential of the earth as V is above it. Electricity will pass from the prime conductor to D, till D is charged to the potential V, and then no more electricity will pass. In the second case D will also be at zero potential, but the potential of the prime conductor will be $V + V^1$. Hence the difference of potential between prime conductor and D will be greater, and a greater flow will take place. It will be found later on that the spark we can get depends on the difference of potential. We should therefore expect much longer and more powerful sparks in the second case than in the first, and such is the fact.

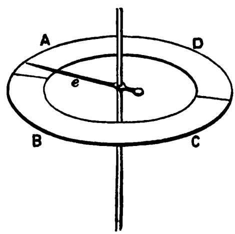


Fig. 57.

136. Measures of potential all depend upon the fact that a body always tends to move in the direction in which the potential falls off most rapidly. Let ABCD (fig. 57) be a ring composed of two metals, copper and zinc, soldered together, lying in a horizontal plane, and *e* a wire capable of motion about a vertical axis, and charged positively. Its potential is positive. It is found that the needle rotates from the zinc to the copper; shewing that

the difference between the potentials of the copper and needle is greater than between zinc and needle. Again, when the needle is in connection with a negatively electrified body it turns towards zinc; proving that the potential of zinc is positive to that of copper when the two are in contact. It is by an arrangement somewhat similar to this that Sir William Thomson's quadrant electrometer acts. It will be more fully described later on, but the following is a description of the part of special interest at present. It consists of a cylindrical box divided into four quadrants, ABCD (fig. 58), completely separated from one another and insulated, but connected by wires diagonally, A with C and B with D. A flat plate, E, is suspended so as to be capable of turning about a vertical axis, in a plane parallel to the surface of ABCD, and in equilibrium takes up the position indicated by the figure. It is kept charged to a constant potential by an arrangement to be more fully described hereafter. The quadrants A and C are connected with the earth, B and D with the conductor F, whose potential is to be measured, and they at once acquire the potentials of the earth and conductor F respectively. If the potential of F be +, E will move so as to have more of its surface covered by A and C than by B and D, and will take up a position of equilibrium when the torsion of the wire just equals the force tending to make E move. When the potential of E is large compared with that of the conductors whose difference of potential is being ascertained, the torsion can be shewn to be proportional to this difference. If the potential of F be −, the deflection is the other way.

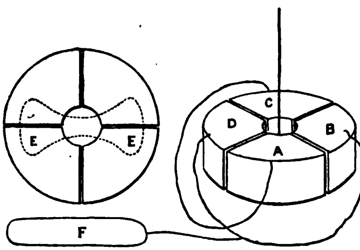


Fig. 58.

137. Again, both experiment and the mathematical investigation of electricity go to shew that the phenomenon of

induction depends entirely on a difference of potential between the conductor inducing and the conductor on which a charge is induced. That is, where two conductors are at the same potential, whatever it be, no induction takes place by the one on the other.

CHAPTER IX.

FRICTION ELECTRIC MACHINES.

138. The requisites in a *machine* of this nature are a large surface, to give a great amount of electricity, and some arrangement to collect it and render it available. This portion of the machine is denominated the *prime conductor.* The rubbed surface of the electric machines is either a

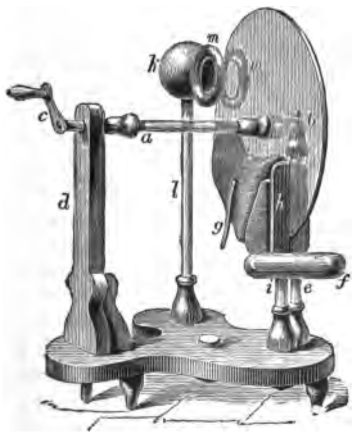


Fig. 59.

cylinder or a plate of glass ; hence we distinguish them into cylinder machines and plate machines. The former, from their more compact form, are the more manageable ; and the latter, from both sides of the glass plate being rubbed, are the more powerful forms of the instrument.

139. *Plate Machine.*—The description of Winter's plate machine (fig. 59) will be sufficient to shew the general requirements and construction of electric machines. It was designed by Carl Winter of Vienna. The first machine on this principle in this country was made under the superintendence of Dr Ferguson of Edinburgh in 1858. It is one of the best existing forms of the machine. The glass plate is turned on the axis *ab*, by means of the handle *c*. The longer end of this axis, consisting of a glass rod, moves in the wooden pillar *d*, and the other rests in the wooden head of the glass pillar *e*. The plate is thus completely insulated, and little loss of its electricity can take place through its supports. The two rubbers (fig. 60) are triangular pieces of wood, covered with a padding of one or two layers of flannel, inclosed in leather, and they present a flat hard surface to the glass, so that friction between it and them takes place in every part. They are placed in a wooden frame on each side of the plate, and the pressure is regulated by metal springs. Before use, they are covered, with the aid of a little grease, with an amalgam of mercury, zinc, and tin, which increases immensely the production of electricity. The surfaces of the rubbers are conducting, and communicate by strips of tinfoil with the *negative conductor*, *f* (fig. 59). To prevent the electricity of the glass from discharging into the air, before reaching the prime conductor, each rubber has a non-conducting wing; this consists of several sheets of oiled silk, kept together by shell-lac varnish, beginning at the rubber with several, and ending with one or two sheets. When the machine is in action, these become negatively electrified, and are attracted by and adhere to the glass, and so diminish the attraction between the charges on the glass and the rubber; but when it is out of action, they may be kept up by a split pin, *g*. As the plate turns, the rubbers are kept in the frame by their ledges, *h*. The whole frame-

Fig. 60.

work of the rubbers and negative conductor can be insulated when required. The prime conductor, *k*, is a brass ball insulated on the long glass pillar *l*; and to prevent the edges of the ball at the junction dissipating the electricity, the pillar enters the ball by a trumpet-shaped opening. The electricity is collected from the glass by a row of points placed in grooves, inside of two wooden rings, *m*, *m*, which are attached on each side of the plate to a piece of brass projecting horizontally from the ball of the conductor. The grooves are covered with tinfoil, which conveys the collected electricity to the ball, and the points are kept out of the way of injury by not projecting beyond the grooves.

A section of the ball of the prime conductor is shewn in fig. 61. There are four openings into it: the lower one for

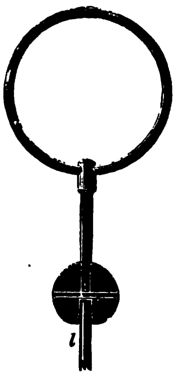


Fig. 61.

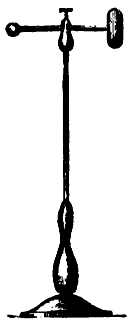


Fig. 62.

the head of the supporting pillar; the one at the right for the attachment of the collecting apparatus; the one at the left for the stalk of a small brass ball; and the upper one for admitting the lower end of a large wooden ring, removable at pleasure. The last forms the peculiar feature of Winter's machine. It consists of an iron wire bent into the shape shewn in the figure, carefully covered all round with polished wood, and communicating with the prime conductor by a brass pin at the foot of the stalk on which it stands. The

value of this addition depends upon its great capacity, because it acts like a Leyden jar (sect. 157). To receive the sparks from the machine, the spark-drawer (fig. 62) is provided. This consists of a wooden pillar of the same height as the prime conductor, in the head of which a brass rod slides, with a large flat ball at the one end and a small ball at the other. All the fittings of the machine are of wood, metal being used only for the prime and negative conductors, and thereby much loss is prevented. The insulating pillars should be, if possible, of green glass, which, from the absence of lead, is less conducting than flint glass. It is desirable, likewise, to cover them with shell-lac varnish, which prevents the formation of a conducting layer of moisture on them from the atmosphere. As the plate is turned, $-$ E is developed on the rubbers, and led to the negative conductor, and thence to the ground; and $+$ E is formed on the glass, which, as it recedes from the rubber, acquires a high potential. Negative electricity is induced on the points, so that when the electrified glass comes close to them, the mutual attraction of the opposite electricities is sufficient to overcome the insulation of the air; a discharge takes place; the prime conductor is charged positively, and the greater portion of the charge on the glass is neutralised. If the negative conductor were insulated, the mutual attraction of the electricities of both conductors would act inductively on each other, so that the $+$ E of the prime conductor would be to a considerable extent bound by the $-$ E of the other conductor. It is explained in sect. 135 why electricity is obtained more readily when one of the conductors is connected with the ground. If $-$ E is wanted, the negative conductor is insulated, and the prime conductor connected with the ground, when sparks of $-$ E are given off by the negative conductor.

140. The source of the electricity in the case of friction electric machines is the extra work required to turn it when it is producing electricity, due to the attraction between the separated electricities. Any portion of the glass, as it passes from the rubber to the spikes and round again to the rubber, has a greater quantity of electricity on it between the rubber and the spikes than in the rest of its course, and conse-

quently it will be seen that there is more work done in overcoming the electric attraction than is done by them in the reverse journey.

141. The influence of the large flat ball of the spark-drawer is of importance. Long sparks do not necessarily imply a very powerful machine, but they guarantee good production of electricity. For the generality of electric experiments, sparks of one or two inches are amply sufficient. These, Winter's machine gives readily without the ring; and when occasionally long sparks are wanted, the extension of the prime conductor can be added without inconvenience. It might be supposed that while the long sparks pass, the machine works more powerfully than at other times; but such is not the case, for if the machine be working at the same rate, the long spark occurs at much longer intervals than the short ones. All the forms of disruptive discharge are accompanied with the peculiar odour which arises from the production of ozone, a modification of oxygen.

142. *Cylinder Machines.*—Fig. 63 represents a cylinder machine. A is the glass cylinder; E, the negative conductor, insulated on a glass pillar, D, which can be adjusted by the screw, in the sole of the instrument. The rubber is attached to the negative conductor, and the flap of oiled silk, KK, to the rubber; G is the prime conductor, insulated on the glass pillar, H, and provided with a comb of pointed teeth to collect the electricity; B, B, are the wooden standards in which the axis of the cylinder works. The rest of the machine is sufficiently explained by the figure.

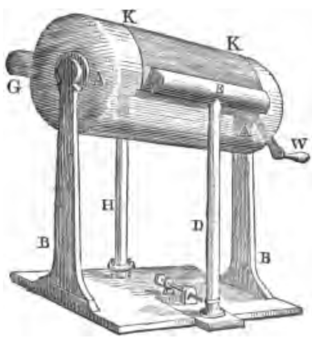


Fig. 63.

143. *Electrophorus.*—This generally consists of a tin mould,

A, which in practice is kept in connection with the ground, filled with shell-lac or resin, B, and a movable metal cover, C, with a glass handle, D, as shewn in fig. 64. The shell-lac is poured in when melted, and it is mixed with some other substance, to make it less brittle. Five parts of shell-lac, one of wax, and one of Venice turpentine, are given as a good mixture. The surface of the resin or shell-lac is smartly beaten with cats' fur. This electrifies the resin negatively. When C is brought near B, it is charged positively on its under surface, negatively on its upper. If then it is touched, the negative escapes, and C is charged with + E; and if removed and applied to any conductor, it will give a positive charge to it. The process may be repeated for a great number of times with only a small diminution of B's charge, except by connection or dampness. It is usual to have the earth connection made by a metallic pin passing through B to A, or by a piece of tinfoil pasted extending slightly over B, and connected with A. In removing C charged from the neighbourhood of B, extra work is done against the mutual attraction of the charges. This is the equivalent of the energy of electrification obtained.

Fig. 64.

144. *Electrical Discharge—Glow—Brush—Spark.*—As the charge upon any conductor is increased, the electromotive force tending to overcome the resistance of the dielectric becomes greater and greater, until at length the dielectric gives way, and a discharge takes place in the form of a more or less luminous, noisy, and hot spark. The electro-motive force necessary to produce a discharge depends among

other things upon the nature of the dielectric. In the case of air, it diminishes with the density until a certain rarity is reached, and afterwards increases enormously as the rarefaction is continued. The term disruptive discharge is applied to all cases where discharge is attended by a permanent or temporary rupture of the dielectric, accompanied with light, sound, and heat. The concomitant phenomena of sound, light, and heat also vary with the capacity of the conductor. All the forms of discharge may be well shewn with the aid of a good electrical machine. When the conductor, which we shall suppose connected with a machine in working order, terminates in a point, there is always a great accumulation of electricity at the point, giving rise thereby to a great *resultant* force tending to infinity. Before this limit can be reached, the dielectric gives way, and allows the electricity to be discharged into the neighbouring parts of the dielectric. In the case of air, the particles in the immediate neighbourhood of the point are electrified by this discharge with the same electrification as the point, and are then immediately repelled: their place is occupied by non-electrified particles, which are also immediately electrified and repelled, and thus a constant electric discharge takes place between the point and the surrounding atmosphere. The repelled particles fly off in almost continuous streams, and discharge themselves on oppositely or non-electrified bodies. The pointed conductor may therefore be said to discharge itself by convection. The currents of air produced are often strong enough to blow out the flame of a candle.

When the room in which the experiments are made is darkened, there is seen about the point a constant glow, due to the intense heat produced in the air by these discharges. The energy of the discharge takes the form partly of heat, partly of light, sound, &c. The glow may be increased or diminished by aiding or preventing the currents of the repelled particles. This passage of electricity from one place to another is called electrical convection or convective discharge. The glow may be seen on the tops of masts and lightning conductors; also upon the surface of the Holtz machine (sect. 149) in the neighbourhood of the points.

145. The electric brush is the name given to the luminous appearance of the discharge of electricity when the conductor is not pointed, but of small capacity, usually a small ball. Here, as in every case, the discharge takes place when the electromotive force of the charge is sufficient to overcome the resistance of the dielectric. Even with the best machines, a finite amount of time is required to charge a small conductor sufficiently to produce this effect. Hence the discharges take place at small intervals of time and in small quantities—thus producing a greater luminous appearance and little noise, but no current of air. The brush presents the appearance of a bush, which is formed by the successive discharges breaking off into ramifications, as it passes from the one conductor to the other.

146. When the capacity of the conductor is greater, longer intervals of time are necessary to charge it to the necessary potential than in the case last considered; and accordingly, when the discharge takes place, a larger quantity of electricity passes in the form of a spark, and a much greater effect is produced. The light is often very intense, and the noise loud and sharp.

147. Sir W. Thomson measured with an electrometer the electromotive force necessary to produce a spark across strata of air of different thicknesses, between two surfaces, one slightly convex, the other plane. He found that for distances of about a millimetre and under, the electromotive force increased with the distance, but in a less rapid ratio.

148. The appearance of the spark varies with the distance between the plates, and also with the medium. When the distance is small, the spark is comparatively straight, but gets more forked and crooked or zigzag in form as the distance increases, and beyond a certain distance, varying with the capacity of the conductors, it takes the form of the brush discharge. Professor Tait and Mr A. Mathieson of Edinburgh University have recently photographed sparks from a powerful Holtz machine. From these photographs it is seen that the sparks in many instances are not merely deflected from their course, but double back upon it as in fig. 65. Again, they often bifurcate, and after travelling some dis-

tance separate and again unite. They have also shewn that the cause of the abrupt change of direction of the spark is probably due to germs, &c. floating in the atmosphere, because when the discharge was made to take place in air

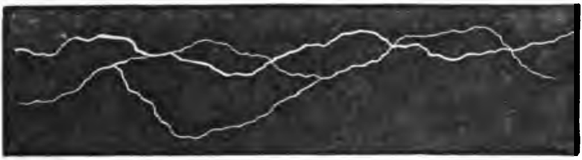


Fig. 65.

heated by being previously passed through a considerable length of red-hot tube, for the purpose of destroying these germs, the path was almost free from these jagged points and other peculiarities.

Holtz and other Electro-Static Induction Machines.

149. One great objection to an ordinary friction machine like that described in sect. 139, is that there is a great waste of energy in overcoming the friction. In recent years, several instruments have been invented which work rather on the principle of the electrophorus, and in them the energy spent in driving the machine is almost all transformed into electricity.

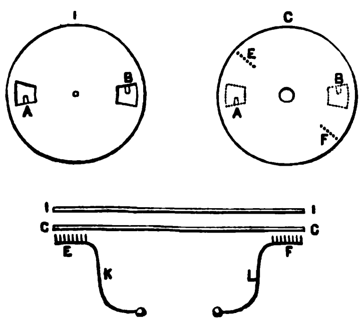


Fig. 66.

They all consist essentially of one or more insulated conductors, movable and fixed: the former are usually called carriers; the latter, inductors, &c. We shall give a detailed description of one, and mention some others. In the Holtz machine the inductor, I (fig. 66), is a circular glass plate with two apertures cut near the

circumference, to the edge of which a pointed piece of paper, A and B, is fixed. The carrier, C, is another plate of same dimensions, turning on an axle. Near the side of the carrier, remote from the inductor, are two combs, E and F, for collecting the electricity. The paper A is charged negatively, say, by a piece of excited vulcanite, and induces $-$ E on the outer surface of C in its immediate neighbourhood, $+$ on the inner side. We may suppose the carrier to be composed of a number of sectors, one of which we shall examine as C is turned round. When it is opposite A, it has $+$ E on its inner surface, $-$ E on the

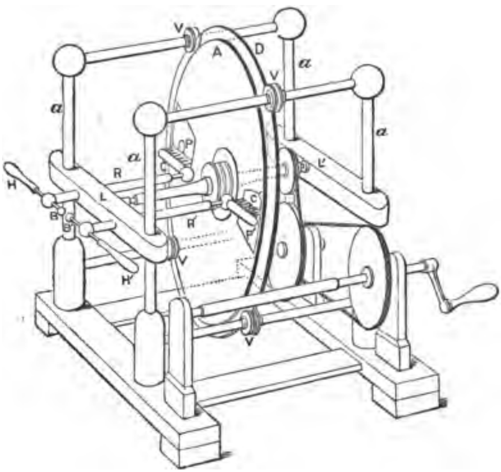


Fig. 67.

outer. On coming to E, the negative E is carried off by E; and a little farther on, B is charged $+$ by drawing the $+$ from the inner side of C. Then a new separation takes place by inductive action of B, $+$ being now on the outside of C, $-$ on the inside. At F the comb draws off the negative again, and A gets a fresh charge of $-$ and a further separation ensues. But what is true of the small region is true of the whole surface of C—that is, the separation, &c. goes on continuously.

The distance between the balls can be varied at pleasure, and by attaching Leyden jars to K and L, their capacity can be made very great, and large sparks of several inches in length can be obtained.

In fig. 67 is shewn a complete Holtz machine with a single revolving plate. D is the inductor, and A the revolving plate mounted on the axis L L′, which runs in sockets fixed in the cross-pieces of vulcanite, L and L′. P and P′ are two pieces of paper glued to the glass, the one on the upper and the other on the lower side of the window-holes. C C′ are the collecting combs connected with the spark-drawing balls B and B′ by the brass rods R and R′.

150. *Discharge by Points and Flames.*—When the machine is in action, and sparks of several inches in length are passing, they instantly cease when a sharp metal point held in the hand is presented to the machine at some distance from the prime conductor. The reason is that the electricity on the prime conductor induces an opposite charge on the rod, which accumulates at the point so as to produce an enormous electric density there. The mutual attraction which ensues is sufficient to overcome the insulation of the dielectric, and the charge of the prime conductor is drawn away continuously, instead of by successive discharges of much larger quantities. It is on the same principle that a lightning rod discharges a thunder-cloud of its electricity, silently and without a flash. If a pointed rod be placed on, or connected with, the prime conductor, no spark can be got from it; powerful currents of air proceed from the point, sufficiently powerful to turn a small wheel furnished with paper vanes, or to blow away the flame of a candle, as in the *electric glow* discharge, due to the repulsion between the charged point and the air in its neighbourhood charged by contact. This is generally shewn by taking a wire pointed at both ends, and bending it so that its points are at right angles to it and on opposite sides of it, and poising the whole on a point on the machine. When the machine is in action, the points are driven backwards, and the wire revolves on the principle of a reaction wheel. In the dark, the points describe a luminous ring from the glow at them.

151. When the flame of a candle is held near the machine, it acts like a point; if uninsulated, it acts more decidedly than when insulated. In the latter case, it appears to point towards the machine and out from it, acting like a double point—one discharging the machine, the other discharging the flame into the air. Professor Guthrie describes experiments which throw light upon the nature of the influence exercised by flames as dischargers. He shews that, whether the flame be a luminous or non-luminous one—that is, whether it be charged with solid matter or not—it discharges an electroscope with equal rapidity when held above it. That this is not due to the currents of air produced by the flame, is shewn by the fact that currents of air, either cold or hot, blown from a bellows on an electroscope, do not discharge it. He thinks the heat relieves the strain of induction by the thermal agitation of the molecules, which allow the charge of the electroscope to dissipate; and this again gives rise to heat, which further aids the discharge. It is also due to the vibration of the molecules by heat that he attributes the non-reception or non-retention of a charge, even for an instant, by an insulated and white-hot iron ball. As it cools, it acquires at a red-heat the power of receiving and retaining a negative charge, and at a lower temperature charges of either kind. These variations are partly due to the apparent preference of air for + over − E. He finds too that an earth-connected iron ball discharges equally, when white-hot, an electroscope charged positively or negatively; but as it cools to dark-heat, it is found to discharge one negatively electrified, but not positively.

152. The *heat of the spark* is shewn by holding a spoonful of ether below the small projecting ball so as to receive a spark from it. The spark instantly kindles the ether.

153. A person standing on an *insulating* stool (that is, a stool with glass legs), with one hand on the machine, can with the other send sparks to everything and everybody about him. In this position he can kindle ether, or light with his finger a jet of gas. The most extraordinary experiment that can be performed with Winter's machine is the lighting of a gas-jet by a person wholly unconnected with

the machine, and standing some eight or ten feet from it. If the person so situated holds the blade of a knife or other point over the gas-burner, at a distance only short of touching, at each long spark from the machine, a small spark passes between the blade and the burner, and thus ignites the gas. The reason is as follows: The body of the person in question is electrified negatively by the extensive prime conductor of the machine acting inductively. When the spark passes, the ring is discharged, and its inductive power for the moment ceases; and the negative electricity of his body, now no longer attracted by it, returns to the ground, and taking the easiest route, causes the spark in question. This is quite similar to what is known in thunder-storms as the *back-stroke.* A person in a prominent position, under a highly charged cloud, experiences a violent, sometimes fatal shock at the same time as a flash of lightning, although the flash was not at all near him.

The *physiological effect* of the spark may be felt by any one holding the back of his hand near the machine so as to get a spark from it. A ten-inch spark from Winter's machine produces a stinging sensation accompanied by a nervous twitching, and this may be felt by a dozen persons at once, joined hand in hand, the first presenting his free hand to the machine, and the last having his free hand connected with the ground or negative conductor.

CHAPTER X.

ACCUMULATORS.

154. An *accumulator* is the name given to an apparatus for receiving and retaining large quantities of electricity. It consists essentially of two conducting plates, separated by a layer of non-conducting material which is called the dielectric. Thus two parallel sheets of metal separated by air form an accumulator. Also any insulated conductor may be regarded as an accumulator, the other plate being represented by the walls of the room in which

it is placed, and the intervening air being the dielectric. A common form of accumulator, first adopted by Franklin, is made by coating a pane of glass on both sides with tinfoil, with the exception of a margin about two inches wide all round. Another form employed by Faraday in his researches on *specific inductive capacity* consists of a metallic sphere surrounded by a concentric spherical shell, also of metal, and of slightly larger radius, the space between being filled with air or other dielectric substance.

An accumulator is charged by putting one of its plates, usually called the receiving plate, in connection with the prime conductor of an electric machine, while the other is connected with the earth. Let A and B be the two conducting plates, parallel to each other, and separated by a layer of air; and let A be insulated, and B in connection with the ground. Suppose a positive charge of electricity to be given to A. This, acting on B through the air as dielectric, will induce a negative charge on the side of B next to A; and, if the charge of A be continually increased, a corresponding increase in the negative charge of B will take place. This will go on till a certain limit is reached, when the electricity of A begins to escape through the air and by its insulating support. The accumulator is then said to be fully charged. The quantity of electricity accumulated in this way will depend upon the area of the plates, their difference of potential, and the thickness of the dielectric.

By the *capacity* of an accumulator is meant the quantity of electricity which must be communicated to the receiving plate to produce unit difference of potential between the two plates. Other things being the same, the capacity will vary with the specific inductive capacity of the dielectric employed. If the specific inductive capacity of air be taken as unity, and C represent the capacity of an accumulator with air for the dielectric, then, if K denote the specific inductive capacity of another substance, the capacity of the same accumulator with that substance substituted for air will be represented by KC.

155. The capacity of an accumulator formed of two parallel plates is calculated as follows:

Let A and B, fig. 68, be the two plates whose potentials are V and V′ respectively, and whose areas are each equal to S. Also let the distance between them, or the thickness of the dielectric, be t. Except near the edges, which may be neglected if the plates are large in comparison with their distance apart, the lines of force, for this case, will be perpendicular to both plates, and hence the tubes of force will be cylinders. Now it is known that if R be the resultant force at any point, and ω the area of the section, perpendicular to the direction of R, of the tube of force at that point, the product $R\omega$ is constant. Hence, as ω is constant for a cylinder, so must R be constant. The value of R vanishes for points within the plate A, and since its value changes by the quantity $4\pi\sigma$ (where σ is the surface density) on passing through an electrified surface, its value just outside the surface must be $4\pi\sigma$. Therefore,

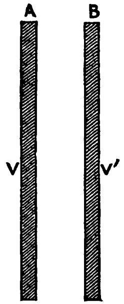


Fig. 68.

$$R = 4\pi\sigma.$$

But R is also equal to the rate of change of potential per unit of length between A and B—that is, to $\dfrac{V-V'}{t}$.

Therefore $$R = 4\pi\sigma = \frac{V-V'}{t}.$$

Therefore $$\sigma = \frac{V-V'}{4\pi t}.$$

But Q, the quantity of electricity on A, is $S\sigma$.

Therefore $$Q = S\sigma = \frac{(V-V')S}{4\pi t}.$$

But the capacity, C, is the quantity of electricity necessary to produce unit difference of potential.

Therefore $$C = \frac{S}{4\pi t}.$$

If the plate B be connected to the earth, $V' = O$ and $Q = \dfrac{VS}{4\pi t} = CV$.

If a plate of shell-lac or vulcanite whose specific inductive capacity is K be inserted between A and B, then $Q = KCV$.

156. As it is an important case, we shall also find the capacity of a sphere, A, surrounded by a concentric spherical shell, B (fig. 69), both being insulated.

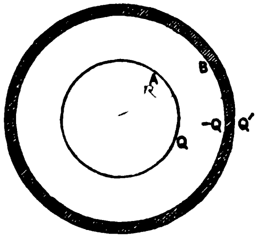


Fig. 69.

Let r be the radius of A, R the radius of the inside surface of B, and x the thickness of B. Let a quantity, Q, of electricity be distributed over the surface of A. This will induce a quantity $-Q$, on the inner surface of B, the complementary $+Q$ going to the outer surface of B. The potential at every point within the sphere A is the same as at its centre. Let it be V; then,

$$V = \frac{Q}{r} - \frac{Q}{R} + \frac{Q}{R+x}.$$

The potential just outside B is the same as if Q were collected at the centre. Therefore, calling it V',

$$V' = \frac{Q}{R+x}. \quad \text{Therefore subtracting,}$$

$$V - V' = \frac{Q}{r} - \frac{Q}{R} = Q . \frac{R-r}{Rr}.$$

Therefore $Q = \frac{Rr}{R-r}(V - V')$. But when $V - V' = 1$, $Q = C$.

Therefore $C = \frac{Rr}{R-r}$.

157. By far the most useful form of accumulator is the Leyden jar, so named from the place of its discovery. The discovery was accidentally made in 1746, by Cuneus, a pupil of Muschenbroek, while endeavouring to give an electrical charge to water. He took a wide-mouthed glass flask partially filled with water, and, holding it in his hand, allowed a chain, hanging from the prime conductor of an electrical machine, to dip into the water. The machine was then worked for some time, and on taking hold of the chain to remove it from the water, Cuneus was surprised to feel

a smart shock pass through his arms. He describes the shock as very severe; but no doubt its extreme novelty led him greatly to exaggerate its severity. In this experiment Cuneus had unconsciously made an accumulator whose dielectric was the glass, and whose conducting plates were respectively his hand and the surface of the water next the glass.

The Leyden jar, as usually constructed, consists of a glass jar (fig. 70) with a coating of tinfoil carefully pasted inside and out, extending to within a few inches of the mouth. The mouth is generally closed by a wooden stopper, through which passes a brass rod surmounted by a brass ball or knob. The connection between the inside coating and the ball is made by a chain extending from the lower end of the brass rod to the bottom of the jar. If this jar be put upon an insulating stool, and sparks drawn to the knob from the prime conductor of the machine, it will be observed that, after a few sparks have passed, no more will follow although the machine be worked; or, if they do, they are immediately dissipated from the knob in a brush discharge. If then, however, the knuckle of the experimenter be brought near the outer coating, sparks begin again to pass freely, and for every spark which passes between the machine and the knob a similar spark passes between the knuckle and outer coating. This continues for some time, and then the jar is fully charged. The action of the jar is as follows: The $+$ E communicated to the inner coating by the machine acts inductively through the glass on the outside coating. It produces a charge $-$ E on the inside of that coating, the complementary positive charge going to the outside. It is this complementary $+$ E which is observed to pass to the earth when the knuckle is applied to it. As the inside coating of the jar forms nearly a closed surface, the charge on its outer surface is very small, consisting only of the electricity on the knob and brass rod and chain.


Fig. 70.

If the glass of the Leyden jar be thin, the curvature of the

jar may be neglected, and hence, it may be regarded as an accumulator consisting of two parallel plates. We can, in consequence, apply the result of section 155 in order to find its capacity. Let Q be the quantity of electricity given to the inside coating, whose area is S, V and zero the potentials of the inside and outside coatings respectively, t the thickness of the glass, and K its specific inductive capacity; then $Q = \frac{VKS}{4\pi t}$. Hence, if C be the capacity of the jar, $C = \frac{KS}{4\pi t}$. This can be put into the form $\frac{S}{4\pi \frac{t}{K}}$, which shews that the capacity of the jar is the same as that of a similar jar with air of the thickness $\frac{t}{K}$ instead of glass for the dielectric.

158. The Leyden jar is discharged by establishing a conducting connection between its inner and outer coatings. This is usually done by an instrument called *discharging tongs* (fig. 71), which consists of two brass arms ending in balls, and movable on a hinge by glass handles. One of the balls is placed on the outer coating, and the other brought round to the knob. When this is done, a brilliant flash, accompanied by a sharp snap, is seen to pass between the knob and the approaching ball. If the discharge is made through the body by laying the hands simultaneously on the knob and outside coating, a violent shock is felt. A charged Leyden jar obviously represents a store of potential energy; and the amount of this energy which is transformed into heat, light, sound, &c. by the discharge of the jar is, by section 131, equal to $\frac{1}{2}QV = \frac{1}{2}CV^2$, and is thus proportional to the square of the potential of the inner coating. When a Leyden jar is charged, it is a question whether the opposite electricities reside on the surfaces of the tinfoil coatings next the glass, or on the surface of the glass itself. To test this, Franklin devised the experiment of the jar with movable coatings.

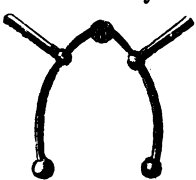


Fig. 71.

This jar, which in shape resembles a common tumbler, is so constructed that its coatings, although fitting closely to the glass, can be easily removed and replaced. In making the experiment, the jar is charged in the ordinary way. The inside coating is first removed and discharged by touching it with the finger; the glass is then lifted out of the outside coating and placed on an insulating stand; the outside coating is now discharged, and the whole is put together again. When the discharging tongs are applied, a bright spark and snap is produced. This shews clearly that—at least, during the time when the glass jar was separate from its coatings—the electrical charges must have been on its inside and outside surfaces.

159. *Residual Charge.*—If a large Leyden jar be fully charged, allowed to stand for some time, and then discharged, it will be found to re-charge itself to a small extent in the same way as before. This is observed on connecting its two coatings by the discharging tongs, when a considerable spark takes place, followed sometimes by as many as four similar discharges, each less than the preceding, and all from the same initial charge. These, called *secondary discharges*, are attributed to what is known as the *residual charge* of the Leyden jar, and this again is referred to the phenomenon of *electric absorption* observed in glass and other solid dielectrics. When the jar is strongly charged, the glass seems to have soaked up to a small depth below its surface a certain quantity of the opposite electricities, which it again allows to ooze out after discharge has taken place. It is the quantity thus oozing out which re-charges the jar, and produces the secondary discharge. Although dielectrics behave as if they absorbed electricity when under strong polarisation, it does not follow that they actually do so. If they did, as has been observed by Clerk-Maxwell, the fact could not fail to be detected by the following experiment: Let the dielectric substance be surrounded by a metallic vessel well insulated. Let it then receive a charge of electricity, and immediately let the outside vessel be discharged and again insulated. Now, if any electricity had been absorbed by the substance of the dielectric, and were now being given out, it would certainly

charge the outside of the metallic vessel in such a way as to be manifest to the ordinary delicate tests. No such charge has ever been observed, and hence no real electric absorption can have taken place. A different explanation of electric absorption has been given by Clerk-Maxwell. By a mathematical investigation, he shews that no such phenomenon can take place in a strictly homogeneous dielectric; and by a similar investigation he shews that it must take place, provided the dielectric be heterogeneous; and that it will not matter whether the heterogeneous dielectric be disposed in layers, each in itself homogeneous, or consist merely of a conglomeration of particles. It will readily be seen that this explanation amply accounts for the phenomenon in glass and solid dielectrics generally.

160. *Discharge by Alternate Contacts.*—If a Leyden jar be charged and insulated, it can be gradually discharged by alternately touching the knob and outer coating with the finger. At each contact a feeble spark takes place. Suppose Q to be the entire charge on the inner coating. Part of this will be on the outside of that coating, including the knob, brass rod, and chain; and part on the side next the glass. Let x be the fraction of Q, which is next the glass; then $-x$Q will be the charge on the outer coating, which was in connection with the ground. Hence, $-x$ is the coefficient by which we must multiply the charge on the inner coating at any time, in order to get the charge on the outer coating at the same time, that coating being at zero potential. Similarly, let $-x'$ be the coefficient by which we must multiply the charge on the outer coating, insulated, to get the charge on the inner coating when it is at zero potential. Now let the knob be touched; the charge on the inner coating immediately after will be got by multiplying the charge on the outer coating by $-x'$; that is, it will be $+xx'$Q. Next let the outer coating be touched, and similarly the charge on it immediately after will be got by multiplying the charge on the inner coating by $-x$; that is, it will be $-x^2x'$Q. Hence, we see that the charge on either coating after any contact is got by multiplying the charge on the same coating after the previous contact by xx'; that is to say, the charges

left form a geometric series, whose common ratio is xx'. The quantity removed from the inner coating after n contacts will be:

$$Q\,(1 - x^n x'^n);$$

and from the outer, $\quad -xQ\,(1 - x^n x'^n)$.

Since x and x' are fractions very nearly equal to unity, the quantity removed at each contact is very small, and, theoretically speaking, it would require an infinite time to remove the whole.

This method of discharge is prettily illustrated by a toy called the electric spider. A ball connected with the outer coating is placed at the distance of one or two inches from the knob, and a piece of pith made up so as to resemble a spider is hung by a silk thread between them. The spider keeps moving between the two balls under the influence of the opposite electricities alternately on the knob and outside coating.

161. In order to find the specific inductive capacity of different substances, Faraday made use of two precisely equal and similar accumulators, in one of which the dielectric was air, and in the other the substance, whose specific inductive capacity he wished to determine. One of his accumulators is represented in fig. 72. It consists of a metallic sphere A, attached to the knob M by means of a rod passing through a plug of shell-lac. A is surrounded by a concentric spherical shell B, made in two halves, which can be separated so as to allow different solid dielectrics to be included between A and B. The diameter of A is 2·33 inches, and the distance between the surfaces A and B ·62 of an inch. By means of a stopcock R, the space between A and B can be exhausted of air, and filled with different gases. The two accumulators are used as follows:

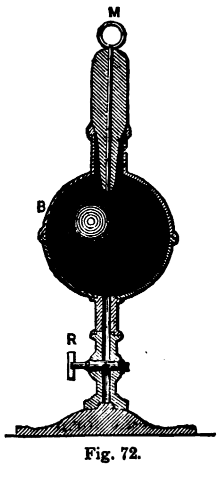


Fig. 72.

Denote them by X and O respectively. X is first filled with air and O with the substance, such as shell-lac, whose specific inductive capacity it is required to determine. Let K denote this; then, if C be the capacity of X, the capacity of O will be KC. A charge of electricity is given to X by the knob M, the outside of B being in connection with the earth. If V be the potential of A, the quantity of electricity communicated to it will be CV. Now, let the knob, M, of X be joined to the corresponding knob of O, which is uncharged. The charge of X will be divided between X and O; and if V′ be the common potential, we have, since the quantity of electricity is the same as before, the equation

$$V'(C + KC) = CV.$$

From this, $$V' = \frac{V}{1 + K},$$

whence $$K = \frac{V - V'}{V'},$$ which determines K.

As an example, take one of Faraday's experiments on shell-lac. The initial potential of X, as ascertained by Coulomb's torsion balance, was 290°. When X and O were joined the common potential was 114°. Hence,

$$K = \frac{290 - 114}{114} = \frac{176}{114} = 1{\cdot}54.$$

When different gases were put into O, X containing air as before, Faraday found that in all cases the common potential V′ was equal to $\frac{1}{2}$V, from which it follows that the value of K for all gases is unity (sect. 108).

162. *Electric Battery.*—In order to get a great accumulation of electricity, large surfaces are necessary. This can be obtained either by constructing a large jar, or by uniting several small jars together so as to act as one. The latter method is preferable, as we can vary the surface according to the number of jars employed. A number of small jars united together as one is called an *electric battery.* A very convenient form of electric battery is shewn in fig. 73. The knobs of each jar communicate with a large central one by means of arms of brass moving on hinges, and the outer coatings are put in conducting connection by being placed on an insulated stool covered with tinfoil. The interior

coatings are conveniently charged by a long projecting arm from the central knob, and the exterior ones by connecting

Fig. 73.

the stool with the ground. Any jar can be thrown out of action by throwing back its arm.

If there be n equal jars in the battery, each of capacity C, it is clear that the capacity of the battery will be nC, since the total amount of coated surface is n times the surface of a single jar. If the battery be charged to potential V, the quantity, Q, of electricity accumulated will be nCV, and the energy which is equal to $\frac{1}{2}QV$ will be $\frac{1}{2}nCV^2$.

Let the n jars be insulated and so arranged that the knob of the first jar is connected with the machine, and its outer coating with the knob of the second, and the knob of the third with the outer coating of the second, and so on, the outside of the last being in connection with the earth. This is called charging *by cascade;* and the whole is discharged by bringing the knob of the first in connection with the outer coating of the last. Let C be the capacity of each jar, and V the potential of the knob of the first. The difference of potential between the knob and outer coating of each jar will be $\frac{V}{n}$, and the quantity of electricity accumulated in it,

$\frac{CV}{n}$. Hence, the whole charge in the n jars is CV, the same as if one alone had been charged in the ordinary way. The potential energy will be $\frac{1}{2}CV \cdot \frac{V}{n}$, that is $\frac{1}{2}\frac{CV^2}{n}$.

Again let the n jars be each charged separately in the ordinary way. Then let the knob of the first be put into connection with the outside coating of the second, the knob of the second with the outside of the third, and so on. This is called charging *in series.* Let C be the capacity of each jar, and V the potential to which it is raised before contact with the others. When the connections are made, the potential of the second will be 2V, of the third 3V, and so on, the potential of the nth being nV. If we compare this arrangement with the ordinary electrical battery, we find that, since the electromotive force—that is, the difference of potential—is nV instead of V, the striking distance is much greater in the former than the latter. The quantity of electricity, however, is less, being CV instead of nCV. The potential energy for this case is $\frac{1}{2}CV \cdot nV$, that is $\frac{n}{2}CV^2$, and so is the same as for the battery. This was to be expected, since it requires the same amount of work to charge n jars separately as n jars together to the same potential, their outside coatings being in connection with the earth.

Experiments with the Leyden Jar or Battery.—By discharging the Leyden jar or electric battery through particular channels, we obtain some beautiful illustrations of the power of electricity. When the discharge is effected through thin wires of gold or platinum, the heat accompanying its passage is so great as to dissipate them in vapour. The expansion of the air caused by the spark is shewn by the *electric mortar.* This is a wooden mortar with two wires entering air-tight at the opposite sides of the breach, with a small wooden ball fitting closely in the muzzle. The spark passing between these wires in discharge causes a sufficient expansion of the air within the mortar to drive the ball to some distance off. When the discharge is made through gunpowder, it tosses the grains violently about, but causes no

ignition; when, however, it is retarded by introducing an imperfect conductor, such as a wet string, into the circuit, the gunpowder is fired. When the discharge is made through glass by two points pressing against its opposite surfaces, a small hole is drilled into the glass. To assist in such experiments, the universal discharger (fig. 74) is used. This consists

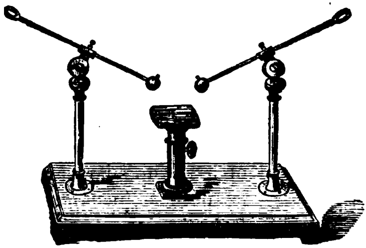


Fig. 74.

of two arms of brass mounted on glass pillars, so that their position and distance can be easily adjusted, and of a small movable table placed between them, the whole resting on a wooden foot. When the discharge of a Leyden jar is made through a number of individuals, each receives an equally powerful shock. The want of insulation here does not cause a loss as when they receive a spark from the machine, for the electricities of the two coatings have each other, not the ground, for their final termination.

163. *Velocity of Electric Discharge.*—The rapidity with which electric discharge takes place is so great, that we might well despair of reaching any definite information about it. Wheatstone, by means of a revolving mirror, determined its rate of propagation in certain circumstances. A small mirror was made to revolve fifty times a second, and the reflection of the electric spark was observed in it. Any one who takes a mirror in his hand and makes it revolve, sees that objects are apparently displaced by it, and it admits of an easy geometrical demonstration, that the reflected image describes an angle the double of that of the mirror. If, while the small mirror rotates at this rate, the image of a spark

should shew a displacement of 90°, we know that the mirror has moved through 45°, and the time during which this takes place is $\frac{45}{360}$ of $\frac{1}{20} = \frac{1}{160}$ of a second. If the duration of the spark, then, had been $\frac{1}{160}$ of a second, we should have seen its image move through 90°. The eye, however, during this time would not have been able to discern any difference between the beginning and the end of the spark, so that the 90° would have appeared as one arc of light. Examined in this way, however, the spark of a machine and that of a Leyden jar were seen as if the mirror had been at rest. Thus analysed with an apparatus where a duration of $\frac{1}{36000}$ part of a second would have shewn an arc of 1°, the electric spark appears instantaneous. The discharge of a Leyden jar through a long wire is not so instantaneous. Wheatstone's method of finding this was as follows: Six balls (fig. 75) were arranged in pairs, each pair being quite near the other. The ball 2 was connected with 3 by a copper wire a quarter of a mile in length, so were also 4 and 5—the dotted lines in the figure marking simply the connection. When discharge took place, the electricity of the inner coating was communicated to 1, and of the outer coating to 6. Supposing charge to travel from the inner to the outer coating, it would proceed from 1 to 2 by spark, then by the long copper wire to 3, by spark to 4, by the other long wire to 5, and by spark to 6. To the eye, the three sparks seemed simultaneous. In the mirror, however, they presented the appearance of three arcs of equal length, the middle one rather behind the others (fig. 76). In this instance, the mirror revolved 800 times a second, and the retardation of the middle line was about ¼°. The time, therefore, taken by the discharge to travel from 2 to 3, or 5 to 4, a quarter of a mile, was $\frac{\frac{1}{4}}{360} \times \frac{1}{800} = \frac{1}{1,152,000}$ of a second, which corresponds to 288,000 miles per second; greater than the velocity of light,

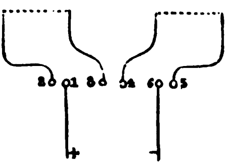


Fig. 75.

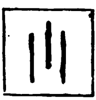


Fig. 76.

which is only 194,000 miles per second. In the same manner, it was calculated from the lengths of the arcs, which were 24°, that the duration of each spark was $\frac{1}{24000}$ of a second. It thus appeared that the discharge was a successive one, not, at least, as instantaneous as through a short conductor.

CHAPTER XI.

ELECTROSCOPES AND ELECTROMETERS.

164. Strictly speaking, an electroscope is an instrument which merely indicates the difference of electric potential between two conductors, whereas an electrometer is one which not only indicates but also measures the amount of that difference in terms of the proper unit, although the one is often used for the other. They both depend for their action upon the effects produced by electrostatic force acting between two conductors, one of which is usually fixed and the other movable. The movements of the latter are, in electrometers, registered on a suitable scale, and the corresponding differences of potential can be compared with each other, or, if desired, expressed in absolute measure by multiplying by the proper constant.

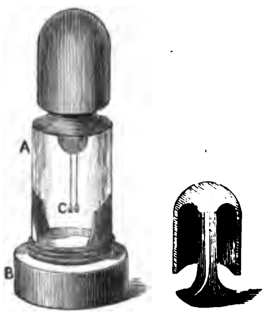


Fig. 77.

The most simple example of a rough electroscope is the electric pendulum already described (sect. 51). A more delicate instrument is the double pendulum electroscope of Cavallo (fig. 77.) It consists of two pith balls suspended side by side by fine silver wires, and inclosed in a glass case, which is surmounted by a bell-shaped cover in metallic contact with the wires. When an electrified body is brought near the bell-

shaped covering, the balls become similarly electrified and repel each other.

The most delicate and useful instrument on the double pendulum principle is the gold leaf electroscope of Bennet. It is represented in fig. 78. A is a glass vessel closed by the metal support, B. At C are seen two strips of gold leaf gummed to the parallel faces of a flat piece of brass. This piece is attached to a stout brass rod, which passes up through an insulating plug in the neck of the vessel, and carries the brass disc, D. Close to the glass, on the inside, is a cylinder of wire gauze, H, which is tall enough to surround the gold leaves. This essential addition was first made by Faraday, and it is strange that since that time the instrument has been often used without it, and the defect not realised. It is obvious that the motion of the gold leaves, C, will depend upon the difference of potential between them and the inclosure, H; and hence the importance of keeping H at a definite potential, as by connecting it with the ground through the sole-plate. If H be removed, and the surface of the glass only be exposed to the gold leaves, the indications of the instrument become unreliable, as the potential of the glass surface may be inconstant. In these circumstances it is not even an electroscope, as the leaves might diverge when the difference of potential to be tested was *nil*. Besides giving a definite potential, the wire gauze H serves the important purpose of screening the gold leaves from the action of all external electrified bodies.

Fig. 78.

165. Sir William Thomson has divided electroscopes and electrometers into two great classes—the *idiostatic* and the *heterostatic*. In the former, only one electrification is made use of—namely, that which is being tested or measured; in the latter, besides this, an auxiliary electrification is employed, supplied from some independent source, such as a charged

Leyden jar. The electroscopes already mentioned are examples of the *idiostatic* class. Of the *heterostatic* class, the simplest example is the Bohnenberger electroscope represented in fig. 79. It consists of a single strip of gold leaf, *f*, suspended symmetrically between the opposite poles, P and P′, of a dry pile (sect. 192), the whole being inclosed in a glass jar, C. A permanent difference of potential is maintained between P and P′; P, let us suppose, being the positive and P′ the negative pole. When *f* is neutral, it will remain stationary between P and P′; but if it be electrified, let us say, positively, through the knob, D, it will be simultaneously repelled by P and attracted by P′. The opposite will be the case if *f* be negatively electrified. It is this double action which gives great sensitiveness to instruments of this class.

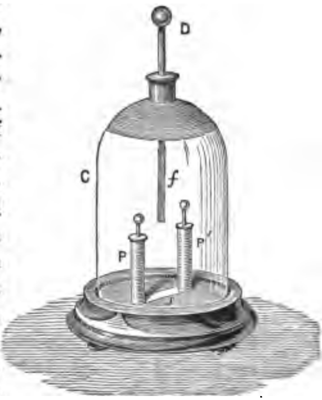


Fig. 79.

166. *Absolute Electrometer.*—This is an instrument for determining differences of potential in absolute measure—that is, in terms of the fundamental units of length, mass, and time. To understand theoretically how this is done, suppose A and B to be two horizontal circular discs of metal placed face to face, one above the other, and separated by a narrow space. Let A be undermost, insulated, and kept at a constant potential V by being in contact with a Leyden jar. Let B be suspended by a wire from one arm of a delicate balance in connection with the ground, and consequently at zero potential. In the other scale of the balance let a weight, *w*, be placed such that it will just balance the attraction of A for B, and keep them at the distance *d* apart. Now, neglecting the influence of the electrification on the un-

opposed faces of A and B, and the want of uniformity in the electrical distribution near their edges, we have the equation

$$4\pi\sigma = R = \frac{V}{d},$$

where R is the resultant force at a point between A and B, and σ the surface density. Also the attraction between the discs per unit of area is $2\pi\sigma^2$. Therefore if S be the area of the lower disc, A, we have, since the attraction is equal to the weight w,

$$wg = 2\pi\sigma^2 S = 2\pi S\left(\frac{V}{4\pi d}\right)^2 = \frac{SV^2}{8\pi d^2},$$

where g is the acceleration produced by gravity.

Therefore $$V = d\sqrt{\frac{8\pi wg}{S}} \qquad (1),$$

which expresses V in absolute measure.

Now, suppose the disc, A, to be detached from the Leyden jar and put in contact with a body at potential V′. Keeping everything else the same, let A be moved parallel to itself up or down till the attraction between A and B at distance, d', is again just balanced by w, then

$$V' = d'\sqrt{\frac{8\pi wg}{S}} \qquad (2).$$

Subtracting (2) from (1), we have

$$V - V' = (d - d')\sqrt{\frac{8\pi wg}{S}}.$$

From this we see how the difference of potential between two bodies can be determined by getting the difference of two distances on a scale, and multiplying by a constant.

The above principle of the attracted disc was first employed by Sir W. Snow Harris, and has been adopted by Sir William Thomson in the construction of his *absolute electrometer*.

167. *Thomson's Absolute Electrometer.*—This is a heterostatic instrument, and can be viewed as consisting of two distinct

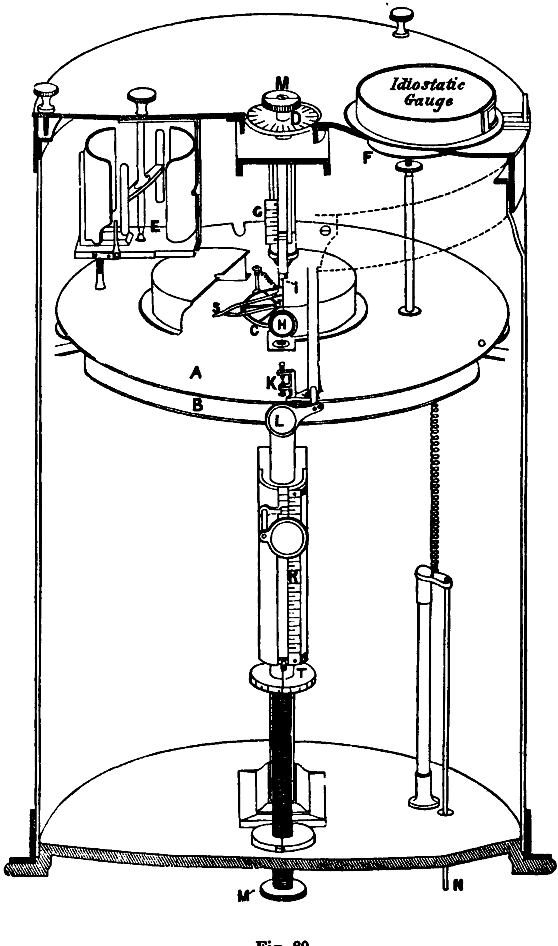


Fig. 80.

J

parts. One of these is for testing and maintaining a certain constant auxiliary potential V, and the other for determining, in absolute measure, the difference between the potentials of any two given conductors. The first of these parts embraces a *Leyden jar*, forming the case of the instrument, an *idiostatic gauge*, and a *replenisher*, E (fig. 80). The Leyden jar is a cylinder of white flint-glass, closed at top and bottom by metal plates. It is coated inside and out to within a short distance of the top with tinfoil, openings being left where necessary for viewing the internal parts. The *idiostatic gauge* will be understood from fig. 81. P is a small square plate of aluminium, which just fills, like a trap-door, without touching the edges, a square hole in the metal plate, G. One side of the aluminium plate is drawn out and bent so as to form a handle to it, *h*, exactly like a spade. Through the bend at the part of the handle next the spade passes a platinum wire, *f*, which is stretched between two supports attached to G. The torsion of this platinum wire, which is bent out of the straight line over a slight projection at the point where it passes through the handle, regulates the motions of the aluminium plate. The fork, F, at the end of the handle passes over a white enamelled projecting piece of metal, which has two black dots upon it near together, and in the same vertical line. Across the end of the fork is stretched a black hair, whose motion up and down in front of the enamelled projection is watched through the lens, *l*. It is so arranged that, when the plate P has its surface in the same plane with that of G, the hair is seen straight, and exactly between the two black dots. This is called the sighted position. At F (fig. 80) is seen a circular disc, supported on a metal rod rising from the disc A, which is in contact with the inner coating of the Leyden jar. F is thus

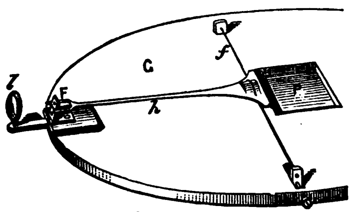


Fig. 81.

always at the same potential as this coating,—that is, at the value V. The disc F is fixed opposite to, and below, G, when the gauge is in its proper position; and the distance between F and G is so regulated that, when the potential of F is V, its attraction for the aluminium plate, P, is such that it just overcomes the torsion of the platinum wire, and keeps P in the sighted position. In this way the constancy of the potential V is tested. To keep V constant is the object of the *replenisher* seen at E.

This is, in reality, a small electrical machine worked on the Holtz principle (sect. 149). It is represented with the revolving axis detached in fig. 82. A and B are two bent pieces of metal called inductors. They are placed so as to deviate a little from being parts of the same cylindrical surface. Attached to them are two springs, *a* and *b*, called the receiver springs. C and D are other two springs, called contact springs, in metallic communication with each other, but insulated from the rest of the machine. P and Q are two curved pieces of metal called carriers, fixed to a cross-piece of vulcanite, which is attached to the axis, T, also of vulcanite. This axis, when in position, can be twirled round by the milled head, E, so that the carriers, P and Q, revolve inside the inductors, and successively touch the springs, *a*, D, *b*, C. When the replenisher is in its place in the electrometer, the inductor, A, is put in metallic connection with the plate, A (fig. 80), and in consequence with the inner coating of the Leyden jar; while B is similarly connected with the outer coating by being in contact with the cover of the jar. A has therefore the auxiliary potential, which it is desired to keep constant. To see how this is done, let us suppose the

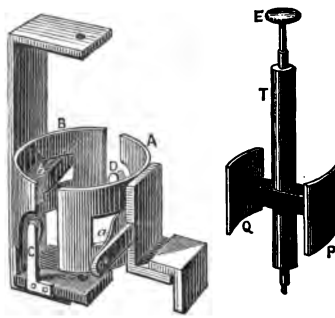


Fig. 82.

axis, T, to be turned round in the direction opposite to the hands of a watch held with its face upwards, from the position where P is in contact with the spring D. At that point, A being + electrified, P will receive a − charge by induction through the air-space separating A and P; while Q will receive the corresponding + charge. When P comes in contact with *b*, it is practically within a closed conductor, and so will give up its − charge to B. At the same time Q gives up its + charge to *a*, and hence, by each turn of the axis, the difference of potential between A and B is increased by a certain quantity. The reverse will be the case if T is turned in the opposite direction. In this way, by simply turning the replenisher in one direction or the other, the potential of the jar can be raised or lowered at will, and so kept at the value V, as indicated by the *idiostatic gauge.*

The second distinct part of the electrometer consists of the attracted disc arrangement, whereby differences of potential are expressed in absolute measure. A (fig. 80) is a circular plate of metal called the *guard-plate*, in metallic contact with the inner coating of the jar. At its centre is a circular opening which is just filled, without touching, by the movable disc, C. This is about 46 millimetres in diameter, and is made of thin aluminium, flat and smooth on the lower side, but stiffened by a projection round the rim and radial arms on the upper side. C is supported by three symmetrically placed steel springs, one of which is seen in the figure at S. These springs resemble in shape very much the merrythought of a fowl. One prong of each is attached to the centre of C, and the others to a brass piece cemented to the end of a glass rod seen at I. This glass rod is attached to a metal piece which is moved up and down in properly constructed guides by the micrometer screw, M. The movements of the screw are registered by the scale G, and the graduated disc, D.

Attached to the centre of the attracted disc, C, is a fine hair, in front of which a lens, H, is so placed that it forms an image of the hair at its conjugate focus near the surface of the glass jar. This image is viewed through an eye-piece seen at L. Two screws, K, are so placed that the image of the hair

is seen exactly between their points when the disc, C, is in its sighted position—that is, when its lower surface is in the same plane with the lower surface of the guard-plate, A. B is a metal disc, called the *attracting disc*, insulated from the rest of the jar, and movable up and down by the micrometer screw, M′. B is put into connection with the body whose potential is to be tested by the electrode, N. The movements of B are registered by the scale, R, and the graduated disc, T.

The electrometer is used as follows: First, all electric influence is removed by putting for an instant the electrode, N, and A into metallic connection by a wire passing through the cover. The attracted disc is then brought to its sighted position by M, and the screw reading noted. A known weight, w, is then placed symmetrically upon the disc, so as to depress it a little below the level of the guard-plate. By the micrometer, M, the disc is again raised to its sighted position, the reading noted, and then the weight, w, removed. In one instrument, Sir William Thomson mentions that $\frac{6}{10}$ths of a gramme depresses the disc through a distance represented by two turns and a very small fraction of the screw. The Leyden jar is now charged to potential V as determined by the idiostatic gauge. During each experiment this is kept constant by the replenisher. B is next put into connection with the outside coating by the electrode, N, and the micrometer, M′, is moved till the attraction of B on the balance disc brings it to its sighted position. The attraction of B is then known to be equal to the weight, w. This reading being noted, B is now insulated, and the bodies, the difference of whose potentials, V_1 and V_2, is required, are successively put into contact with B through N. The distances, d_1 and d_2, through which B has to be moved to bring the attracted disc in each case to its sighted position, are determined, and the difference of potential is given by the equation,

$$V_1 - V_2 = (d_1 - d_2)\sqrt{\frac{8\pi wg}{S}},$$

where S is the area of the attracted disc, or more correctly, the mean of the areas of the disc and the circular hole in which it moves.

168. *Quadrant Electrometer.*—This instrument, also due to Sir William Thomson, is by far the most delicate electrometer hitherto invented. It is heterostatic, and consists essentially of the following parts: A *Leyden jar*, a *movable needle*, four *quadrant inductors*, a *replenisher*, and an *idiostatic gauge*. The last two are exactly similar to those already described. The Leyden jar is an inverted glass shade (of white flint-glass),

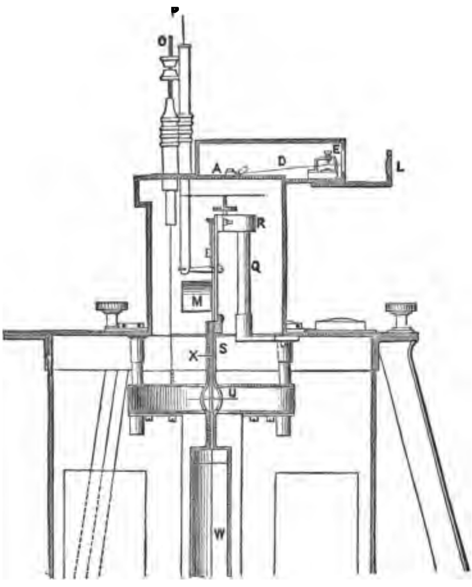


Fig. 83.

supported on three legs from a brass mounting cemented round its rim. A cupful of strong sulphuric acid is put into the glass shade, which serves the double purpose of inner coating to the jar and of keeping the internal parts free from moisture. The outside coating is formed of strips of tinfoil in connection with the brass mounting and metallic supports.

The mouth of the jar is closed by a cover of stout sheet brass, which carries all the internal parts of the electrometer. The instrument is represented in fig. 83, with the lower part removed. Rising from the cover, and over a hole in its centre, is a *lantern*-shaped erection which carries the electrodes, one of which is seen at O, the charging rod, P, and the idiostatic gauge, parts of which are indicated at A, D, E, L.

The movable needle, seen edgewise at U, consists of a thin strip of aluminium shaped like a figure 8, and attached rigidly by its narrow part to the stiff platinum wire, X, the wire being at right angles to the plane of the needle. The wire, X, projects upwards and downwards from the needle. From its lower end hangs a fine platinum wire, stretched by a platinum weight, which dips in the sulphuric acid, and thus puts the needle in conducting connection with the inner coating of the jar. To its upper part is attached the light silvered mirror, M, with its plane vertical; and just above this the wire, X, ends in a small T-shaped piece of metal, to which the two fibres are attached, by which the whole is bifilarly suspended from the projecting brass piece, R, which is cemented to the glass support, Q. At S and W are seen fixed guard tubes, which screen the suspended wire from external electrification, and also serve, by being put into contact with P, to give the original charge to the jar. The four quadrant inductors are represented in fig. 84. They are in reality parts of a flat circular box, cut into four by saw cuts at right angles to each other through its centre. The alternate ones, A and A′, B and B′, are connected by wires. The four are supported all at the same level by glass rods from the brass cover of the instrument. Three of them are fixed by nuts, while the fourth can be moved out and in horizontally by a spring and counteracting

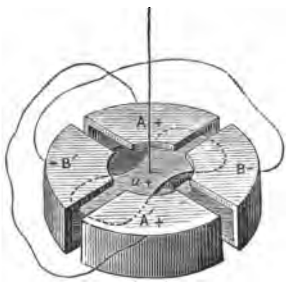


Fig. 84.

screw, and is guided by three rounded projections, two of which move in a V groove, while the third simply slides on the flat surface of the brass support. By this simple kinematic arrangement, the quadrant has only one degree of freedom, and moves with great steadiness. The four quadrants, it will be observed, surround the needle on all sides, as is seen in fig. 84. The motions of the needle, U (fig. 83), which is rigidly connected with the mirror, M, are indicated by the deflections of a spot of light on a distant scale. This spot of light is the reflection from the mirror of the rays of light which fall upon it through a vertical slit from a lamp placed behind the scale. The usual lamp and scale are represented in fig. 85.

Fig. 85.

The action of the instrument is as follows: The Leyden jar is first charged to the auxiliary potential V, as indicated by the gauge. During each experiment, this is kept constant by the replenisher, not seen in the figure. The needle, U, is thus permanently at potential V. If the quadrants, A and A′, B and B′ (fig. 84), be at the same potential, there will be no force tending to turn the needle; but if the potentials of these differ by a quantity ever so little, the needle, U, will turn in a certain direction. This direction will be determined by the following consideration: Let V be the potential of U, A the potential of A and A′, and B that of B and B′; then if the difference between V and B be greater than the difference between V and A, the needle will move so as to oppose a greater part of its area to B than to A—that is, in the direction from A towards B. By a mathematical analysis, it is

found that the moment of the couple tending to turn the needle from A to B is

$$a(A-B)\{V-\tfrac{1}{2}(A+B)\}, \text{ when } a \text{ is a constant.}$$

If, as is usual, V is very much greater than $\frac{1}{2}(A+B)$, the latter may be neglected, and the expression for the couple becomes

$$aV(A-B).$$

From this it will be seen that the sensitiveness of the instrument is increased by making V large.

The instrument is used by putting the bodies, the difference of whose potentials is required, in connection with the quadrants, A and B, through the *chief electrodes*, one of which is O, in fig. 83. The scale readings are then noted, and, within certain limits, these are taken as proportional to the deflecting couple, and in consequence proportional to the difference of potential. To convert the scale readings into absolute measure, they must be multiplied by a certain constant, which is determined experimentally, once for all, for each individual instrument. The quadrant electrometer is extremely sensitive, as is shewn by the fact that it can give a deflection of a hundred divisions on the scale for the difference of potential between zinc and copper.

CHAPTER XII.

TERRESTRIAL AND ATMOSPHERIC ELECTRICITY.

169. *Terrestrial Electricity.*—If the earth were merely a smooth electrified sphere, its surface-density would be uniform all over; if it were, as it is, an oblate spheroid, but smooth and undiversified by hill and dale, the surface-density at any point would be simply proportional to the perpendicular let fall from the centre on the tangent plane at that point. In this case the electric distribution could be easily determined. In the actual case, however, the surface is so extremely irregular, embracing as it does, electrically speak-

ing, the surface of all bodies in conducting connection with the ground, that it would be utterly impossible to determine mathematically the distribution, even supposing it to be constant and uninfluenced by external electrified masses. Speaking generally, however, it may be said that the electric density would be greatest on the hill-tops and on all sharp points and corners; less on extensive plains; and least of all, approaching to zero, on the inside surfaces of all nearly inclosed spaces, such as caves, rooms, and on the ground below trees.

170. The electrification of the earth's surface varies considerably from place to place. In some parts it is negative, in others positive, with neutral lines of equilibrium between them. The negative areas, however, always greatly exceed the positive ones in extent. In calm serene weather the electrification is almost always negative; and if such weather were to prevail for a short time all over the earth, it is conjectured that, for that time, the entire surface would be negatively electrified. The surface electrification also varies very much from hour to hour. This is caused by the inductive action of large electrified masses of air moving not very far above the earth's surface. Such masses moving, for instance, over a level open country, would disturb the uniform distribution of electricity which would naturally be there; and this disturbance could be detected by simultaneous observations of electrometers at stations not very far apart. Such observations have been made by Sir William Thomson in the island of Arran; and he gives a mile or two as the probable height of the influencing masses of air at that particular time and place. In many cases the height must greatly exceed this, and cannot be ascertained, even approximately, without a very special set of simultaneous observations.

Although its surface is usually electrified negatively, the earth is by no means to be regarded simply as a huge conductor, insulated in free space, and having a negative charge. In fact, in the higher regions of the atmosphere the air becomes so rarefied as to be a conductor, and there must be somewhere in those regions a complementary electric dis-

tribution to balance the distribution on the surface. Hence, as suggested by Sir William Thomson, we shall not be far from the truth if we regard the earth's surface, the air, and this high aerial stratum, respectively, as the inner coating, the dielectric, and the outer coating of a huge spherical Leyden jar electrified negatively.

171. *Atmospheric Electricity.*—Several methods may be employed to ascertain the potential at any point in the air. One is to place a sphere of small radius at the given point, connect it with the earth by a fine wire; then insulate it and carry it indoors to an electrometer. The potential indicated will be equal, but of opposite sign, to that of the air at the point. Two other methods have been adopted by Sir William Thomson. In one he uses a burning match supported on the end of a long conductor. The products of combustion continually going off carry with them electricity so long as any difference of potential exists between the conductor and the air surrounding the flame. In this way the potential of the conductor is brought in a very few seconds to be the same as that of the air at the point of the flame. By connecting the conductor with the electrometer, its potential can be found. The other method depends upon exactly the same principle. It consists in insulating on a suitable stand a can of water which has a long nozzle projecting at right angles from its lower part. The can is usually placed in a room near a window, which is drawn up a few inches to let the nozzle project to the outside. Water is allowed to trickle slowly from the nozzle, and each drop as it falls carries with it electricity till the potential of the can is reduced to be the same as that of the air at the point where the water from the nozzle just breaks into drops.

It is to be carefully observed that none of the above methods gives us any information directly about the electrification of the air itself. They merely indicate to us the quantity and kind of the electrification of the earth's surface at the time and place of observation. If we suppose the water-dropping apparatus to be placed in an open plain at the height d above the ground, and if σ be the surface-density at the point, and V the potential as indicated by

the electrometer, expressed in absolute measure, we have $4\pi\sigma = \frac{V}{d}$, which gives $\sigma = \frac{V}{4\pi d}$. It is usual in such observations to express V in terms of the potential of so many Daniell's elements (sect. 197). Thus, by using a lighted match, Sir William Thomson found the value of V for a point nine feet above the ground on a level sea-beach in the island of Arran to be from 200 to 400 Daniell's cells. This gives a resultant force perpendicular to the earth of from about 22 to 44 Daniell's cells per foot of air. The same observer also found that the electrometer invariably shewed a high positive potential in clear weather before and during east wind; and in some cases he was able to predict the approach of east wind from the electrometer indications. There can hardly be a doubt that by-and-by observations on atmospheric electricity will give important aid to the meteorologist in weather prognostication. As yet only one set of continuous observations has been made on atmospheric electricity. This was done at Kew for two consecutive years by means of a self-recording electrometer attached to a water-dropping apparatus. The movements of the index were recorded by photography. These observations amply confirm what was previously known regarding the annual and diurnal variations of atmospheric electricity. They shew that the average potential is greater in winter than in summer; and they clearly point out two daily maxima for each month. In January these occur about ten A.M. and seven P.M.; in July at eight A.M. and ten P.M.

It is only by balloon experiments that we can get any direct information respecting the electrification of the air itself, and of these we have not yet a sufficient number to warrant any reliable conclusions. We can, however, get very important indirect information regarding the air's electrification by observing the variations produced by it in the electric density on the earth's surface.

172. *Lightning.*—The resemblance of lightning to the electric spark was noticed almost as soon as the first spark was seen. Franklin saw that they agreed in light, colour, smell, shortness of duration, and in the property of being

transmitted by metals, which they sometimes fused; and he conjectured that they must also have the property in common of being attracted by sharp points. In 1752, Dallibard in France, acting on this conjecture, erected a long pointed rod, insulated at the lower end, and succeeded in getting sparks from it during a thunder-storm. In the same year, Franklin made his famous kite experiment, which completely proved the identity of lightning and the electric spark. His kite was made of a silk handkerchief stretched on a wooden frame, with a fine metal point in connection with the string. A key was tied to the lower end of the string, and when the kite was elevated during a thunder-storm, sparks were drawn in rapid succession from the key as soon as the conduction of the string was improved through its being wetted by the falling rain.

173. Three kinds of lightning are usually spoken of—namely, *forked-lightning*, *sheet-lightning*, and *ball-lightning*. Forked-lightning is nothing more than a long electric spark passing from cloud to cloud, or from a cloud to the earth. The length has been ascertained to be often over a mile; frequently it is between four and five miles; and in one recorded case it was ten miles. The duration of the flash is excessively short. This is shewn by the familiar fact that a rapidly revolving wheel always appears stationary when illuminated by a flash of lightning. Wheatstone, by means of his revolving mirror, has estimated its duration, and finds that it cannot exceed a millionth of a second. Viewed in such a mirror, the reflection of the flash ought to appear elongated if it lasted longer than that time. The form of the flash is zigzag, and it often appears broken up into two or three forks—whence its name. The bifurcation is easily explained by the spark always taking the path of least resistance. The zigzag is not so easily accounted for. It is destroyed in the case of short sparks by heating the air, which not only removes motes and combustible materials from the air, but also does away with all traces of electrification in it. Hence, as is suggested by Professor Tait, 'the zigzag form of the lightning flash may, in certain cases at least, be due to local electrification, which would have

the same sort of effect as heat in rarefying the air, and making it a better conductor.' *Sheet-lightning* is in all probability merely the illumination of the clouds by a forked flash, which is not directly visible to the eye. It often lightens up only the edges of a cloud, and sometimes the same cloud mass several times in succession. The species of sheet-lightning called *summer-lightning* is always unaccompanied by thunder. It is most likely the illumination produced by a discharge so distant that the sound does not reach us. Almost nothing is known about *ball-lightning*, although its existence is proved by several well-authenticated instances. It has not as yet been imitated by any laboratory experiment. It is said to occur in this way: After a violent explosion of lightning, a ball is seen to proceed from the region of the explosion, and to make its way to the earth in a curved line like a bomb. When it reaches the ground, it either splits up at once, and disappears, or it rebounds like an elastic ball several times before doing so. It is described as being very dangerous, readily setting fire to the building on which it alights; and a lightning-conductor is no protection against it. Ball-lightning lasts for several seconds, and in this respect differs very widely from forked and sheet lightning, which are in the strictest sense momentary.

174. Sometimes highly charged clouds are discharged by heavy falls of rain or sleet, with very little or no accompanying thunder and lightning. In this case, the rain-drops are often so highly charged as to emit sparks just before they reach the ground. When this occurs in the dark, the ground is lit up, and we have the phenomenon of *luminous rain*. An interesting illustration of this mode of discharge was recorded by a French observer in 1879; his umbrella became so electrified by a slight fall of snow, that he was able to draw sparks from it.

When lightning strikes a building, curious effects are often observed. The bell wires are found fused, and marks along their course produced on the walls. When it strikes trees, they are commonly shattered and rent. This is caused, no doubt, by the sudden conversion of their sap into steam. The danger of taking refuge under a tree in a thunder-storm

arises from the fact that the body is a much better conductor than a tree, and will in consequence be preferred by the flash to the height to which it reaches. The best protection from lightning would be a complete coat of mail of thin sheet-copper.

175. *Lightning-Conductors.*—The use of lightning-conductors was first clearly pointed out by Franklin. They are rods of metal attached to buildings, and overtopping them to a certain extent, for the purpose of protecting them from being struck by lightning. To be really effective, they must terminate at the top in a fine point, be themselves good conductors of electricity, and be in perfect connection with the earth at the lower end. They should also be in conducting connection with all masses of metal in the building. Rods of iron or copper are commonly employed, terminating in a platinum or gilded point, to prevent oxidation, and attached at the lower end to a mass of metal, imbedded, if possible, in moist earth. In towns, the water mains form a good and convenient 'earth.' For vessels at sea, the lightning-rod should be connected to the copper sheathing, or to some mass of metal which is constantly immersed. The object of the lightning-rod is not so much to conduct the lightning harmlessly to the ground as to continually drain, by the inductive action of its point, the electricity from the thunder-cloud, and so prevent a dangerous accumulation of electricity in it. This action is easily illustrated by the experiment of holding a sharp-pointed rod near the prime conductor of an electrical machine, when it will be found impossible to draw a long spark from the conductor, as is the case when the pointed rod is away. The continual drawing which goes on in the actual case is well seen when there happens to be a gap in the lightning-rod. Across this gap a perfect torrent of sparks is seen to pass whenever a thunder-cloud is in the neighbourhood. This is a dangerous experiment even to witness; and more than one incautious experimenter has lost his life by it.

176. When a lightning-rod is acting imperfectly or when there is any very rapid production of electricity, a luminous glow is seen at the point. This is called *St Elmo's fire*, and

was long ago observed on the masts of ships, and on the points of their spears when soldiers were marching during a thunder-storm. Quite recently a remarkable instance of the same kind occurred in Switzerland, when the tops of a whole forest of trees glowed just before a flash of lightning passed, and immediately after were dark.

177. *Back-stroke.*—Besides the accidents to which men and animals are exposed from the direct stroke of lightning, they often suffer severely, even when entirely out of the path of the flash, and at a considerable distance from the point where it reaches the ground. This fact has been known for a long time, and arises from what is called the *back* or *return stroke.* It will be readily understood from the following explanation: Suppose an elongated mass of highly charged cloud to be hovering near the earth, with one end over a man and the other over some exposed point such as a hill-top. The cloud acting inductively on the man will cause, unconsciously to himself, a separation of the electricities in his person; the one kind being attracted to his head, and the other repelled to the earth through his feet. Suppose now the cloud to be discharged by a flash passing from its other end to the hill-top. All inductive action on the man will instantly cease, and the electricities will suddenly recombine, causing the sensation of a shock more or less severe. The shock from this cause is seldom fatal.

178. *Thunder.*—The noise of thunder is just the snap of the ordinary electric spark on an enormously large scale. When a flash of lightning pierces through the air, its heat causes a sudden dilatation of the air in its track. This is succeeded immediately by a sudden compression of the air round the path, which again is followed by a rapid in-rush of the air-particles to fill the vacuum. This explains the origin of the sound. When the sound is reflected repeatedly from clouds, and from masses of air of different densities, echoes are produced which account for the characteristic *rolling* and reverberation often heard during thunder-storms. If the flash be short, or such that the sounds from all parts of its path reach the ear simultaneously, a *thunder-clap* will be heard. If the flash be long and very much zigzag, the

sounds from the various points of its path, having different distances to travel, will reach the ear in succession, and a *peal* of thunder will be heard.

The extreme distance at which thunder is heard is not very great as compared with other loud sounds. Cannon, for instance, have often been heard at a distance of fifty and a hundred miles, but the maximum distance at which thunder is heard does not exceed nine or ten miles. This is accounted for partly by the extreme variations in the atmospheric density produced during a thunder-storm. It is usual to allow five seconds to the mile in estimating the distance of a thunder-cloud by the interval of time which elapses between the flash and the sound; but instances have occurred where the sound of thunder has been propagated far faster than ordinary sounds. Probably the true explanation of this has been given by Sir William Thomson, who has shewn that very likely sound is produced simultaneously at all parts of the air between the discharging cloud and the ground.

179. *Origin of Atmospheric Electricity.*—The source or sources of atmospheric electricity are still involved in complete uncertainty. One source usually named is the electricity produced by the evaporation of water, and another the chemical actions going on in all vegetable growth. Both of these may have some effect; but the true cause is only to be got by a carefully arranged set of experiments on a large scale. In connection with this subject, certain facts are of great importance; such as the fact that cloud-capped mountains have been seen luminous in the dark, and that active volcanoes throw out vapour and smoke which emit lightning flashes. An analogous fact of extreme importance has lately been reported by an observer in Galway. He states thas he has often seen in the spring-time small clouds, evidently highly charged with electricity, start from the hill-tops of Connemara, and discharge shortly after, sometimes into a neighbouring church spire, and sometimes into the sea.

Part III.—CURRENT ELECTRICITY.

CHAPTER XIII.

ELECTRO-MOTIVE FORCE, CURRENT, RESISTANCE, AND ELECTRICAL UNITS.

180. Hitherto we have had to deal with Electricity either as fixed on the surface of non-conductors, or as rigidly in equilibrium on the surface of conductors, so that it had no tendency to pass from one part of the conductor to another. We now come to the consideration of the various phenomena which accompany the transference of electricity from one body to another. This forms a different branch of the science, and is variously called *Galvanism*, *Voltaic Electricity*, *Dynamic Electricity*, *Electro-kinetics*, or simply *Current Electricity*. It took its origin in 1780 from an observation made by Galvani, professor of anatomy in Bologna. While making investigations on the nervous irritability of cold-blooded animals, Galvani discovered by accident that the limbs of a recently killed frog, when hung by the crural nerve on a metal support near an electric machine, contracted convulsively at the recurrence of each spark. This he properly accounted for on the principle of the *back-stroke* (sect. 177). Six years afterwards, in experimenting on atmospheric electricity with frog limbs as delicate electroscopes, he obtained—also accidentally—the same convulsions by bringing the copper hook on which the nerve hung and the limb itself simultaneously in contact with an iron railing. Galvani attributed these effects to electricity in the limb itself. Volta, on the other hand, in 1792, after carefully repeating these experiments, and making many additional ones on the same subject, came to the conclusion that the convulsions were due to electricity produced at the surface of contact of the heterogeneous metals. In beginning this part of the subject, we must first

get clear ideas about the terms *electro-motive force, current,* and *resistance.*

181. *Electro-Motive Force, Current, Resistance.*—If two insulated bodies, A and B, at the same potential, be joined by a conducting wire, no electricity will pass between them; but if the potential of A be greater than that of B, part of the electrification of A will pass to B, and their potentials will become immediately equalised. This is analogous to the case of two reservoirs of water connected by a pipe. If the two be at the same level, no water will run through the pipe; but if one be higher than the other, a current will flow through the pipe till the level of the water in both be the same. It will make the matter clear if we calculate for a particular case the fall of A's potential, and the quantity of electricity transferred from A to B. Let then A and B be two insulated spheres of radii a and b respectively. Also let A denote the potential of A, and B that of B. Then, since the capacity of a sphere is equal to its radius (sect. 130), the quantity of electricity on A will be Aa, and on B, Bb. Let them now be joined by a fine wire, so as to equalise the potential, and let the common potential be V. Since electricity obeys the law of continuity, or, in other words, behaves like an incompressible fluid, the joint charge on both balls will be the same as before. This gives

$$\mathrm{V}\,(a+b) = \mathrm{A}a + \mathrm{B}b.$$

Therefore
$$\mathrm{V} = \frac{\mathrm{A}a + \mathrm{B}b}{a+b} \qquad (1).$$

Therefore the fall of A's potential being A — V, is equal to

$$\mathrm{A} - \frac{\mathrm{A}a + \mathrm{B}b}{a+b} = \frac{b}{a+b}\,(\mathrm{A}-\mathrm{B}) \qquad (2).$$

Also the quantity of electricity transferred from A to B being equal to

$$\mathrm{A}a - \mathrm{V}a = (\mathrm{A}-\mathrm{V})\,a = \frac{ab}{a+b}\,(\mathrm{A}-\mathrm{B}) \qquad (3).$$

From this we see that, other things being the same, the quantity of electricity transferred depends upon the difference of potential A — B. This difference is called the *electro-*

motive force acting between A and B, and is clearly equal to the amount of work which would be required to carry a unit of negative electricity from A to B against the electrical attraction.

In the case supposed, the transference of electricity would take place in a time so short as to be altogether inappreciable, and we would have a *transient current.* It would also evidently be an ever-weakening current, inasmuch as the difference of potential is continually getting less; and to render the current *steady*, it would be requisite to have some means of keeping the difference of potential between A and B constant. This is the function of the voltaic battery, different forms of which will be described later.

Supposing a steady current to be maintained by some means between A and B, we have next to inquire as to the *direction* and *strength* of such a current. The *direction* is defined by saying that the current always flows from places of high to places of low potential; but it must be kept in mind that this is a mere convention, and that there is no reason, experimental or other, for saying, in the case supposed above, that positive electricity flows from A to B, any more than that negative electricity flows from B to A. According to Weber's hypothesis, a current consists of equal quantities of positive and negative electricity passing in opposite directions through the same conductor.

By the strength of the current between A and B is meant the quantity of electricity which flows through any section of the connecting-wire in a unit of time. If we denote the strength by C, and employ the electro-static system of measurement, then C is measured by the number of electro-static units of electricity which passes any section of the wire in a second. The value of C is found to depend not only upon the electro-motive force A — B, but also upon the material of which the wire is composed, being greater for good and less for bad conductors of electricity. This is shewn as follows: Let two points, A and B, be kept at a constant difference of potential, so that a steady current, C, flows from A to B along a wire joining the two. Also let this wire be homogeneous, and at the same temperature

throughout. At any two points of this connecting-wire join on two other wires of the same material, and lead them to an electrometer. The electrometer will indicate a certain difference of potential, denoted, let us suppose, by E. Now, if we take the ratio of E to C for all pairs of points on the wire, and also for wires of different thicknesses, we find that it varies directly as the length of wire between the two points and inversely as its cross section. If we put this in the form of an equation, calling l the length and ω the section of the wire, we get $\frac{E}{C} = \frac{kl}{\omega}$, where k is a constant depending on the material of the wire. This quantity $\frac{kl}{\omega}$, which depends only upon the length, section, and material of the connecting wire, is called its *resistance*, and is usually denoted by R. This gives $\frac{E}{C} = R$, an expression of great importance in electrical science, and which is called, after its discoverer, Ohm's Law.

182. *Absolute Electrical Units.*—In any absolute system of measurement, all quantities must be expressed in terms of the fundamental units of *length*, *mass*, and *time*. In electrical measurements, the fundamental units usually adopted by scientific men, as being the most convenient, are the *centimetre*, *gramme*, and *second*; and quantities expressed in terms of these are said to be expressed in terms of the C. G. S. system of units. From the fundamental units two other systems of electrical units are derived. These are the *electro-static* and the *electro-magnetic* systems; the former being founded upon the electro-static definition of the unit quantity of electricity, and the latter upon the definition of the unit magnetic pole.

The C. G. S. system of units has already been alluded to in Chapter V., and the definitions of the units of velocity, acceleration, momentum, force, work, &c. are there given.

183. *Electro-static System of Units.*—According to this system, we have the following definitions of units:

(1) *Unit quantity* of electricity is that which repels a similar unit quantity at unit distance with unit force.

(2) *Unit current* is that which conveys a unit quantity of electricity through a conductor in a second.

(3) *Unit electro-motive force*, or *unit difference of potential* between two points is the work done on or by a unit of positive electricity, in moving from the one to the other against the electrical resistances.

(4) *Unit resistance* is that of a conductor through which unit electro-motive force between its ends can send a unit current.

(5) *Unit capacity* is that of a condenser which contains unit quantity when charged to unit difference of potential.

184. *Effect of an Electric Current upon a Magnet.*—Before giving the electro-magnetic system of units, it will be necessary to explain an important magnetic effect produced by an electric current in the space surrounding the wire through which it flows. This was discovered by Oersted, and is the effect upon which depends the construction of the instruments commonly used for measuring electric currents. It is this. If a magnetic pole be in the neighbourhood of a conductor carrying a current, it will be acted upon by a force whose magnitude depends upon the strength, and whose direction depends upon the direction of the current. To explain more fully, let AB (fig. 86) be a portion of a

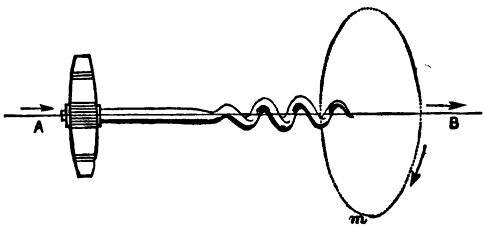


Fig. 86.

straight wire conveying a current in the direction of the arrow, and let m be the north pole of a magnetic needle; then the effect of the current on m is such that m will move round the wire in the circumference of a circle whose centre

is at the wire, and whose plane is perpendicular to the wire. The direction in which m moves is shewn by the arrow, and can in all cases be determined by the following simple rule. Suppose a cork-screw being screwed into a cork in the direction in which the current flows, then a *north* pole will move round the wire in the direction in which the hand is turned to put in the screw. A south pole will move in the opposite direction; and hence it is easy to see that if a magnetised needle be freely suspended near the wire, it will always set itself so as to be at right angles to the wire when in a position of equilibrium.

The force of the current upon the magnetic pole is found experimentally to be independent of the material of the conductor, and to be strictly proportional to the current strength; and hence the reason why this effect is made use of in the construction of galvanometers or measurers of current strength. In what follows, we shall suppose ourselves in possession of a galvanometer whereby currents may be detected and measured. The theory and construction of the instrument will be given in Part IV., after the phenomena of electro-magnetism have been explained.

185. *Electro-magnetic System of Units.*—Keeping in mind the effect just explained, we can understand the following definitions of units in the electro-magnetic system:

(1) *Unit magnetic pole* is that which repels a similar unit pole at unit distance with unit force.

(2) *Unit current* is one which in a wire of unit length, bent so as to form an arc of a circle of unit radius, would act upon a unit pole at the centre of the circle with unit force.

(3) *Unit quantity* of electricity is the quantity which a unit current conveys in a unit of time.

(4) *Unit electro-motive* force is that which must be maintained between the ends of a conductor in order that unit current may do unit of work in a second.

(5) *Unit resistance* is that of a conductor in which unit current is produced by unit electro-motive force between its ends.

(6) *Unit capacity* is that of a condenser which will be at unit difference of potential when charged with unit quantity.

It is of great importance that the student should have clear ideas regarding the various units in terms of which the quantities he is considering are measured. We give here, for the sake of reference, in a collected form, the dimensions of the various units, shewing, at the same time, how the dimensions of the one are derived from those of the other by simple algebraic changes.

186. *Dimensions of Units.*—The meaning of the term dimensions will be best understood from a few examples. Thus:

A *line* is said to be of one dimension.

An *area* being equal to a length × a breadth, that is, the product of two lines, is said to be of two dimensions.

A volume being equal to a length × a breadth × a thickness, is said to be of three dimensions.

A velocity being equal to $\frac{\text{Length}}{\text{Time}} = \frac{L}{T} = LT^{-1}$, is said to be of one dimension in length and -1 dimension in time.

According to Clerk-Maxwell's notation, the concrete unit in terms of which any quantity, whose numerical value is X, is measured, is represented by being inclosed in a square bracket, thus [X]; and the whole quantity is represented by X [X], where X represents the number which specifies how many times over the unit is taken.

FUNDAMENTAL UNITS.

These are the units of length, mass, and time, and are represented respectively by [L], [M], [T].

DERIVED MECHANICAL UNITS.

Velocity is equal to the length gone over in a unit of time. Hence, denoting it by V, we have

$$V = \frac{L}{T} = LT^{-1}.$$

Hence $$V\,[V] = LT^{-1}\,[LT^{-1}]$$

$$\therefore\quad [V] = [LT^{-1}] \qquad (1).$$

Acceleration is equal to the velocity acquired in a unit of time. Hence, denoting it by A, we have

$$A = \frac{V}{T} = VT^{-1}$$

Hence $\qquad A\,[A] = VT^{-1}\,[VT^{-1}].$

$$\therefore \quad [A] = [VT^{-1}]$$

Substituting for [V] its value from (1),

we have $\qquad [A] = [LT^{-2}]$* $\qquad$ (2).

Hence acceleration is of 1 dimension in length and − 2 dimensions in time. Similarly all the following equations are to be interpreted.

Momentum is equal to mass multiplied by velocity. Hence

$$[\text{Momentum}] = [MV] = [MLT^{-1}] \text{ from equation (1)} \qquad (3).$$

Force is equal to momentum generated in a unit of time. Hence, denoting it by F, we have

$$[F] = \left[\frac{MV}{T}\right] = [MVT^{-1}] = [MLT^{-2}] \qquad (4).$$

Work is equal to force multiplied by the length through which it is overcome. Hence, denoting it by W, we have

$$[W] = [FL] = (\text{equation } 4), [ML^2T^{-2}] \qquad (5).$$

DERIVED ELECTRO-STATIC UNITS.

If Q and Q′ be two quantities of positive electricity separated by a distance L, the force of repulsion between them is, by Coulomb's law, $\frac{QQ'}{L^2}$. Denoting this force by F, we have

$$F = \frac{QQ'}{L^2}.$$

Hence $\qquad F\,[F] = \frac{QQ'}{L^2} \cdot \left[\frac{Q^2}{L^2}\right].$

$$\therefore \quad [F] = [Q^2L^{-2}]$$

$$\therefore \quad [Q^2] = [FL^2] = (\text{equation } 4)\ [ML^3T^{-2}].$$

By extracting the square root, that is, dividing each index by 2, we get

$$[Q] = [M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}] \qquad (6).$$

* For shortness in what follows, we shall sometimes omit writing the letters which precede the square brackets, and which stand for numbers. It must be evident, from the examples already given, how they are to be inserted if required.

Current of electricity is equal to the quantity which flows through any section of the conductor in a unit of time. Denoting it by C, we get

$$[C] = \left[\frac{Q}{T}\right] = [QT^{-1}] = \text{(equation 6)}\ [M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}] \quad (7).$$

Electro-motive force is the work done on a unit of electricity in urging it from one point to another. Hence, denoting it by E, and if Q be the quantity moved, we have

$$W = EQ$$

$$\therefore \quad [E] = \left[\frac{W}{Q}\right]$$

$$= \left[\frac{ML^2T^{-2}}{M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}}\right] = [M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}] \qquad (8).$$

Resistance, $\quad R = \dfrac{E}{C}$. Hence

$$[R] = \left[\frac{E}{C}\right] = \left[\frac{M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}}{M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}}\right]$$

$$= [L^{-1}T] \qquad (9).$$

The capacity of a condenser is the quantity of electricity required to charge it to unit difference of potential. Denoting it by K, we have

$$Q = KE$$

$$\therefore \quad [K] = \left[\frac{Q}{E}\right] = \left[\frac{M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}}{M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}}\right]$$

$$= [L] \qquad (10).$$

This shews that capacity is of the dimensions of a line, and this agrees with a result formerly found, viz., that the capacity of a sphere is equal to its radius (sect. 130).

DERIVED ELECTRO-MAGNETIC UNITS.

If two similar magnetic poles, of strength m and m', be separated by a distance L, the repulsive force between them is $\dfrac{m\,m'}{L^2}$. Denoting it by F, we have

$$F = \frac{m\,m'}{L^2}$$

$$F\,[F] = \frac{m\,m'}{L^2}\left[\frac{m^2}{L^2}\right].$$

Hence $$[F] = \left[\frac{m^2}{L^2}\right].$$

$$\therefore \quad [m^2] = [L^2F] = [L^3MT^{-2}].$$

$$\therefore \quad [m] = [L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}] \qquad (11).$$

If a current of strength C, flow in a wire of length L, every part of which is at distance d from a magnetic pole of strength m, the force exerted by the current on m is

$$F = \frac{CLm}{d^2}.$$

Hence $$F\,[F] = \frac{CLm}{d^2} \cdot \left[\frac{CLm}{L^2}\right].$$

$$\therefore \quad [F] = \left[\frac{Cm}{L}\right].$$

$$\therefore \quad [C] = \left[\frac{LF}{m}\right] = \left[\frac{L^2MT^{-2}}{L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}}\right]$$

$$= [L^{\frac{1}{2}}M^{\frac{1}{2}}T^{-1}] \qquad (12).$$

If Q be the quantity of electricity conveyed by a current C, in time T,

$$Q = CT$$

$$\therefore \quad [Q] = [CT] = [L^{\frac{1}{2}}M^{\frac{1}{2}}] \qquad (13).$$

If E be the electro-motive force between the ends of a conductor, and Q the quantity sent through it, the work done is EQ. Hence,

$$[W] = [EQ].$$

$$\therefore \quad [E] = \left[\frac{W}{Q}\right] = \left[\frac{L^2MT^{-2}}{L^{\frac{1}{2}}M^{\frac{1}{2}}}\right]$$

$$= [L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}] \qquad (14).$$

Resistance, $$R = \frac{E}{C}.$$

$$\therefore \quad [R] = \frac{E}{C} = \left[\frac{L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}}{L^{\frac{1}{2}}M^{\frac{1}{2}}T^{-1}}\right]$$

$$= [LT^{-1}] = \qquad (15).$$

From the last equation, we see that the dimensions of resistance are the same as those of a velocity. It will be shewn later how a resistance can be expressed as a velocity.

If we take the two expressions for [Q] given according to the electro-static and the electro-magnetic systems of units, and divide the one by the other, we shall obtain the dimensions of the ratio of the electro-static to the electro-magnetic unit of quantity. Doing this, we obtain

$$\frac{[\text{E.S. unit of Q}]}{[\text{E.M. unit of Q}]}=\left[\frac{M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}}{L^{\frac{1}{2}}M^{\frac{1}{2}}}\right]=[LT^{-1}] \qquad (16).$$

This shews that the ratio of the electro-static to the electro-magnetic unit of quantity is a velocity. This velocity is a very important physical quantity, and is usually denoted by v. Different experimental methods of obtaining it will be described later, and it will also be shewn that, according to Clerk-Maxwell's Electro-magnetic Theory of Light, v is very probably the actual velocity of light.

PRACTICAL ELECTRICAL UNITS.

187. The absolute units of electro-motive force and resistance are so small, and those of quantity and capacity so large, that the quantities with which the practical electrician has to deal, would, if expressed in them, be represented either by inconveniently large numbers or inconveniently small fractions; and hence a practical system of units has been adopted which are certain multiples or submultiples of the absolute units. These are derived from the absolute electro-magnetic units by assuming a larger unit of length and a smaller unit of mass. The large unit of length assumed is 10,000,000 metres, or approximately the length of the earth's quadrant, and the small unit of mass is the $\frac{1}{10^{11}}$ part of a milligramme. The practical units have been named after several eminent electricians. They are as follows:

The *Weber*, the practical unit of quantity $= \frac{1}{10}$ C. G. S. unit.

The *Volt*, the practical unit of electro-motive force $= 10^8$ C. G. S. units.

The *Ohm*, the practical unit of resistance $= 10^9$ C. G. S.

It will be shewn later that the Ohm is equal to a velocity of 10,000,000 metres per second.

The *Farad*, the practical unity of capacity $= 10^{-9}$ C. G. S. unit.

The Microfarad = one-millionth of a Farad, is very commonly used as the practical unit of capacity.

The practical unit current is that of one weber per second. The weber is equal to the quantity of electricity transmitted through one ohm by one volt, and is also equal to the charge produced in a condenser of one farad capacity by the electro-motive force of one volt. The following multiples and submultiples of the practical units are also in use in telegraph working.

The megavolt	=	one million volts.		
" megafarad	=	"	"	farads.
" megohm	=	"	"	ohms.
" microvolt	=	one millionth of a volt.		
" microfarad	=	"	"	farad.
" microhm	=	"	"	of an ohm.

CHAPTER XIV.

VOLTAIC BATTERIES.

188. Having explained the terms *electro-motive force*, *current*, and *resistance*, we come next to consider some of the methods in common use of maintaining a constant electro-motive force between two bodies, and so producing a *steady current* in the connecting wire which joins them. In static electricity we have already had an example of one such method, in the continued flow of sparks which are drawn from the prime conductor of an ordinary friction-machine, or, better still, in the continuous discharge which takes place between the balls of the Holtz machine. By far the most convenient method, however, of producing a steady current is got from the *voltaic pair* or *cell*.

189. *Voltaic Cell.*—When two plates of copper and amalgamated zinc (zinc whose surface has been rubbed over with mercury) are placed in a vessel (fig. 87) containing water to which a small quantity of sulphuric acid has been added, they

remain apparently unaffected, so long as they are kept from touching each other, either within or without the liquid. If, however, they be made to touch, bubbles of hydrogen gas are formed in abundance at the copper plate, and their formation continues until the plates are again separated. If the contact be maintained for some time, and the plates and liquid be afterwards examined, it is found that the copper plate weighs

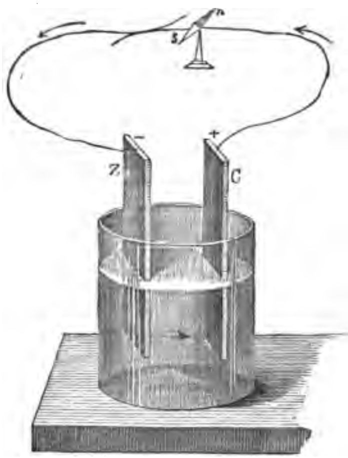


Fig. 87.

exactly the same as before, that the zinc plate has lost in weight, and that the liquid contains the lost zinc in solution in the form of the sulphate of that metal. The chemical action which goes on is represented by the equation $H_2SO_4 + Zn = ZnSO_4 + H_2$. The contact need not be affected by the plates themselves. If wires of copper, or any other conductor of electricity, be soldered to the plates, or fixed to them by binding screws, and be made to touch, the changes just mentioned take place as if the plates were in contact. When the wires are thus joined, and, so to speak, form one connecting wire between the plates, a steady current flows in them, and they exhibit very peculiar properties, which

will be described in their order later on. One such property has already been alluded to (sect. 184).

190. When a number of copper and zinc pairs, similar to the one just referred to, are put together, so that the copper plate of one cell is placed in conducting connection with the zinc plate of the next, in the manner shewn in fig. 88, they constitute a voltaic battery. The term battery is sometimes also applied to a number of cells acting as one combination, in whatever way they may be connected, and sometimes even to one cell. When the terminal copper and zinc plates (fig. 88) are connected, the current runs from each copper to each zinc plate without the liquids, and from each zinc to

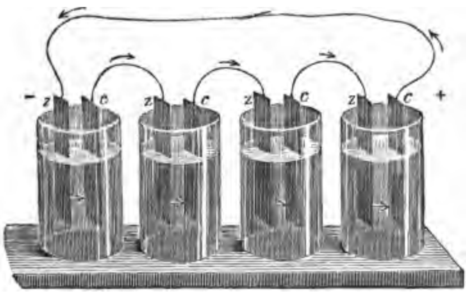


Fig. 88.

each copper plate within the liquids; and when the contact is broken, the zinc pole shews +, and the copper pole − E. The voltaic battery thus put up acts in all respects as a compound voltaic pair, and constitutes a compound voltaic circuit. If two cells be taken, the difference of potential is doubled; if three, tripled; and so on. *The electro-motive force of a battery is therefore proportional to the number of cells,* supposing, of course, that they are arranged consecutively, as in the figure.

The four cells in fig. 88, as stated, form a compound voltaic circuit. They may be made to form also a simple circuit. If all the zincs were connected with one wire, and all the coppers with another, and the circuit completed by one wire,

then the four cells would act in every respect as one cell, whose plates had four times the surface. A battery, such as in the figure, would be said to have a tension arrangement; a battery like the one named, a quantity arrangement.

191. *Volta's Pile* is shewn in fig. 89. It consists of a number of circular plates, each made up of a plate of copper and a plate of zinc soldered together, built up, so that the copper plates face one way and the zinc the other; each compound plate being separated by a circular piece of woollen cloth, moistened with a solution of common salt or dilute sulphuric acid. In consequence of the great number of pairs, the difference of potential of the poles of Volta's pile is considerable. One furnished with from 60 to 100 plates can charge an electroscope without the condensing plates. It is from this battery that the term 'pile' is applied to the voltaic battery. Volta used another form of battery, which he called a *crown of cups*. This consisted of a number of cells like those in fig. 88, arranged in a circle, so that the first and last were contiguous.

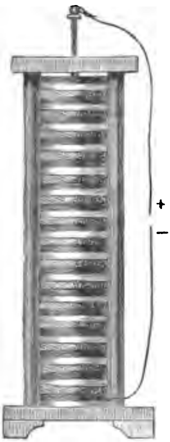


Fig. 89.

192. *Zamboni's Dry Pile* consists of several hundreds, and sometimes thousands, of discs of paper tinned on one side, and covered with binoxide of manganese on the other, put together consecutively, as in Volta's pile, and placed under pressure in an insulating glass tube closed with brass ends, which serve as the poles. The difference of potential of the poles of this arrangement is considerable, but the strength of the current which passes when the poles are joined is next to nothing. The most important application of the dry pile is in the construction of a very delicate electrometer or electroscope, which is named after its inventor, *Bohnenberger's electrometer* (sect. 165). In this instrument the dry pile is insulated, and its ends are placed in conducting connection with insulated wires, which are bent round so as to face each other.

The wires end in small faces, which thus constitute the poles of the pile. A gold leaf is hung between the poles, and turns to the one or the other according as it is charged. As we know the names of the poles, we know at once the name of the electricity with which the leaf is charged, as it must incline toward the opposite electricity.

193. *The Galvanic Trough*, introduced by Cruikshank, is a

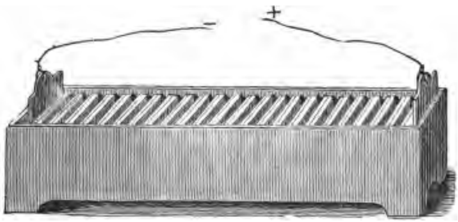


Fig. 90.

trough (fig. 90) into which rectangular plates of copper and zinc, like those of Volta's pile, are fixed, the cells included between each pair being filled with dilute sulphuric acid. The inner surface of the trough is coated with an insulating substance.

194. *Wollaston's Battery.*—Each couple of this battery (fig. 91) is made up of a plate of copper, doubled up so as to include a plate of zinc, from which it is kept apart by strips of wood. Both faces of the zinc are thus equally exposed to chemical action, a device by which the quantity of electricity is increased. Fig. 92 shews a battery of five of these. The connecting strips of metal are fixed to a wooden rod, by which they can be lifted or lowered together. When the battery is put in action, the whole is lowered, and the five couples are immersed in five troughs filled with dilute sulphuric acid (1 of the acid to 12 of water). When out of action, the whole is lifted and fixed by binding screws to the two supporting pillars. When the number of pairs is small, as in the figure, it is of little consequence whether one large trough or five small ones be used.

195. *Smee's Battery.*—In Smee's couple, the position of the

plates of Wollaston's couple is reversed. It consists of a silver plate, with a zinc plate on either side, kept separated from it by slips of wood, the two zinc plates being fastened by a coupling. There are thus two + plates to one —, instead of two – to one +, as in Wollaston's couple. The zinc plates have not thus to be so often renewed as in Wollaston's battery. The silver plate is platinised—that is, covered over with finely-divided platinum—and this is found to lessen the adhesion of the hydrogen bubbles to

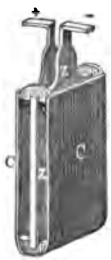


Fig. 91.

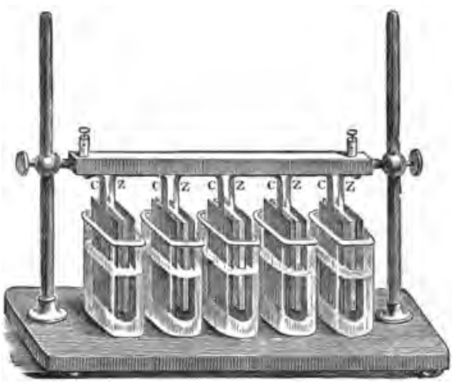


Fig. 92.

the plate, thereby greatly improving the constancy of the action. Smee's battery has the same arrangement as Wollaston's.

196. *Grove's Gas Battery.*—This battery is intended more for instruction than use. One of its cells is shewn in fig. 93. Into the two outer necks of a three-necked bottle, two glass tubes are fitted by means of corks through which they pass. Each of these tubes is open below, and a platinum wire enters them hermetically above; and to this wire a long strip of platinum is soldered, extending nearly to the bottom of the tube. Little cups, containing mercury, stand at the upper ends of these wires. The whole apparatus is filled with slightly

acid water, and the poles of a voltaic battery are placed in the little cups. Water is thereby decomposed: oxygen forms in the one tube and hydrogen in the other. When the battery wires are removed, no change takes place till metallic connection is established between the cups, and the oxygen and hydrogen gradually disappear, attended by an electric current which passes from the oxygen to the hydrogen. When several of these are put together in a battery, the connection being always oxygen to hydrogen, they can decompose water. The most important fact illustrated by Grove's battery is, that the oxygen and hydrogen, liberated by galvanic agency, when left to themselves, produce a current the opposite to that which separated them. When the poles of the decomposing battery are in the mercury cups, hydrogen is given off at the −, and oxygen at the + pole; and as opposite electricities attract, it is manifest that the hydrogen in this action is +, and the oxygen −. When the two gases form, by means of the platinum plates, a galvanic pair by themselves, the current must proceed, as in all cases, from the + to the − within the liquid, and the reverse way between the poles; but this is the opposite of the direction of the original current.

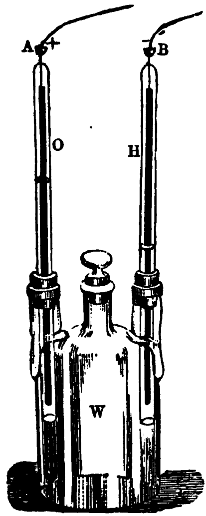


Fig. 93.

Polarisation—Constant Batteries.—It is therefore manifest that where oxygen or hydrogen is set free at any point in a voltaic circuit, it will tend to send a counter-current. This tendency is called *polarisation* of the electrodes. This accounts for the fact, that no single cell can decompose water, as the electro-motive force generated is no greater than that of the counter-current which would be produced by the liberated gases. Even two cells produce an insignificant effect. Polarisation also accounts for the sudden falling off in strength in

all voltaic couples where hydrogen is set free at the negative plate. The bubbles of the gas adhering to the plate, not only lessen the surface of contact between the plate and the liquid, but exert an electro-motive force contrary to that of the pair, and this goes on increasing until the action becomes greatly reduced. In all improved forms of the cell, it therefore becomes necessary to adopt some means of preventing the disengagement of hydrogen at the negative plate, and this is done in all *constant batteries* by employing two fluids instead of *one*. The best known constant batteries are those of *Daniell*, *Grove*, and *Bunsen*.

197. *Daniell's Battery.*—A cell of this battery is shewn in fig. 94, and a section of it in fig. 95. The containing vessel,

Fig. 94.

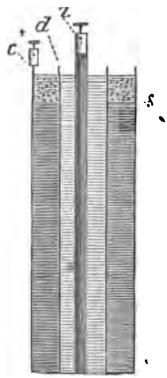


Fig. 95.

c, is of copper, which serves likewise as the negative element of the pair. Inside of this is another vessel, *d*, of porous unglazed earthenware containing a rod of zinc, *z*. The space between the copper and the porous cell is filled with a solution of the sulphate of copper, which is kept concentrated by crystals of the salt lying on a projecting shelf, *s*, and dilute sulphuric acid is placed with the zinc in the porous cell. The rationale of its action is given as follows: The porous cell which keeps the fluids from mingling does

not hinder the passage of the current; when the atoms of hydrogen that would ultimately be freed at the copper reach the porous cell, they displace the copper in the sulphate of copper, and copper instead of hydrogen is thrown on the copper plate. The chemical rationale of the action may be given by the following equations. Beginning with the copper (Cu) of the outer vessel, and ending with the zinc (Zn) of the rod, and taking $|^{d}$ for diaphragm or porous cell, we have the arrangement before discharge $Cu,\overline{CuSO_4}\ \overline{CuSO_4}\ |^{d}\ \overline{H_2,SO_4}\ \overline{H_2,SO_4}\ Zn$; and after it, $\overline{CuCu}$ $\overline{SO_4Cu}\ \overline{SO_4\ |^{d}\ H_2}\ \overline{SO_4,H_2}\ \overline{SO_4Zn}$. The discharge, therefore, effects a deposition of copper at the copper, and the formation of sulphuric acid at the porous cell, and of sulphate of zinc at the zinc rod. Instead of hydrogen in its nascent state being deposited at the copper, we have copper in the same condition; but the polarisation caused by the latter is very much inferior to that resulting from the former, and hence the superior electro-motive force of Daniell's cell. The porous cell keeps the sulphate of zinc from reaching the copper, and thus obviates another source of diminished force in the one-fluid battery. The sulphate of zinc once formed, is itself subjected to the decomposing action of the pile, and zinc is deposited on the copper plate, thus tending to give a zinc-zinc instead of a copper-zinc pair. The constancy of Daniell's battery is not unlimited, for the sulphate of zinc which results from the action, being a bad conductor of electricity, enfeebles the current. From its great specific gravity, however, it falls to the bottom of the cell, and may be removed by a siphon, and replaced by fresh liquid. The copper of the Daniell's cell is frequently also placed inside the porous vessel, as the platinum in Grove's cell. A battery of Daniell's cells is put up in the usual way.

198. *Various Forms of Daniell's Cell.*—Many modifications of Daniell's cell are in use in practical working. The chief of these are the *sawdust Daniell* and *Tray cell*, both due to Sir William Thomson. In the sawdust Daniell, sawdust is made to play the part of the ordinary porous cell. On the bottom of a wide glass vessel is placed a copper plate, to the

edge of which a gutta-percha covered wire is attached, which comes up the side of the vessel and serves as the positive pole. On the top of the copper is placed a layer of moistened crystals of sulphate of copper, and above this a layer of wet sawdust. On the top of this again is spread another layer of sawdust moistened with solution of sulphate of zinc, and on the top of all rests the zinc plate, to which a wire is attached forming the negative pole. This cell is very convenient when portability is required, and was much used by Sir William Thomson during the laying of the Atlantic cable. The element called *Menottis's* is precisely similar to the sawdust Daniell.

The *Tray Cell* consists of a square wooden tray twenty inches long, lined with sheet-lead, on which a layer of copper is deposited by the electrotype process. The zinc plate is made in the form of a grating, to allow the gas to escape, and is supported on blocks of wood at the four corners of the tray. Sometimes the space between the copper and zinc is filled exactly as in the sawdust Daniell. In other cases a sheet of parchment is stretched below the zinc grating, and then the copper solution is supplied from crystals of sulphate of copper lying all round the edge of the tray, while the solution of sulphate of zinc is poured in between the zinc and parchment. The resistance of this cell is very small, being only ·2 ohm. When a strong current is wanted, a number of trays are put the one on the top of the other, the zinc of the one below being in metallic contact with the copper of the next above it.

199. *Grove's Battery* consists of platinum-zinc couples. Fig. 96 shews an excellent arrangement of a cell of it. The outer cell of glass, *g*, is filled with dilute sulphuric acid (1 part of acid to 8 of water), in which a cylindrical plate of zinc, *z*, is immersed. Inside the zinc is a porous cell, *d*, containing concentrated nitric acid and the platinum plate, *p*, which is bent into the form of an S (fig. 97), to increase its surface. In the commonly used form of Grove's cell, the zinc plate is made in the form of a U, and incloses a flat porous cell in which is suspended a strip of platinum foil, attached to the zinc plate by a binding screw. Grove's couple is very

much superior in power to any of the preceding, though it is inferior in constancy to Daniell's. When the poles are joined, sulphate of zinc is formed in the outer cell, and the heavy brown gas, peroxide of nitrogen (N_2O_4), is given off by the nitric acid. As this gas is injurious to the health when breathed for any time, the porous cell is closed with a stopper of wood to prevent or lessen its escape, the connection between the exterior and the platinum plate

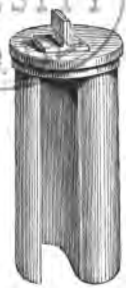


Fig. 96. Fig. 97.

being made by a strip of metal passing through the wood. The chemical action of Grove's couple may be shewn in the same way as Daniell's, taking anhydrous nitric acid (N_2O_5) to be the oxide of the peroxide of nitrogen (N_2O_4,O). Before discharge, the molecules stand thus, beginning with the platinum: Pt, $\overline{N_2O_4,O}\,\overline{N_2O_4,O}\ |^d\ \overline{H_2,SO_4}\,\overline{H_2,SO_4}$, Zn; and after it, $\overline{Pt,N_2O_4}\ \overline{O,N_2O_4}\ O\ |^d\ H_2\ \overline{SO_4,H_2}\ \overline{SO_4,Zn}$. The peroxide of nitrogen discharged at the platinum plate is absorbed by the nitric acid, in which it is soluble, so that the plate is left free. The resulting solution is highly conducting. The peroxide of nitrogen soon spontaneously separates from the nitric acid, giving rise to the dark-brown vapour already mentioned. The cells of a Grove's battery are connected with the platinum of the one to the zinc of the other.

200. *Bunsen's Battery.*—Bunsen's cell has the same chemical action as Grove's, the platinum being replaced by carbon. There are two forms of the cell—the one invented and employed by Professor Bunsen, and generally adopted in Germany; and the modification introduced by Archerau, generally found in England and France. The Bunsen cell, properly so called, has a carbon cylinder immersed in nitric acid, and the porous cell containing the zinc and sulphuric acid placed within it. Fig. 98 represents a battery of four

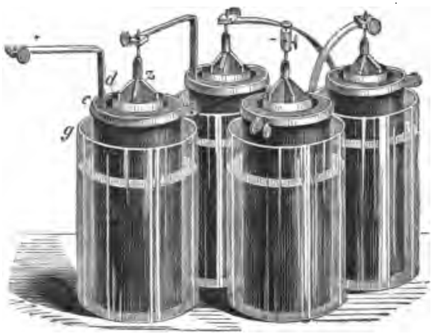


Fig. 98.

cells, shewing how the different cells are connected: *g* is the containing glass vessel; *c*, the carbon cylinder; *d*, the porous cell; and *z*, the zinc. The other form of the Bunsen cell is shewn in fig. 99. In it the same arrangement is adopted as in Grove's cell. Bunsen's battery, in point of cheapness, is preferable to Grove's, where the platinum forms an expensive item, but is inferior to it in point of compactness.

Bunsen Coke.—The carbons for Bunsen's battery are made by a process invented by Bunsen. The fine dust of coke and caking coal is put into a close iron mould of the shape required for the carbon, and exposed to the heat of a furnace. When taken out, the burned mass is so porous as to be unfit for use, but by repeatedly soaking it in thick syrup, or gas tar, and reheating it, it at length acquires the necessary

solidity and conducting power. The carbon that forms on the roof of gas-retorts is harder and better than the carbon thus made, but it is difficult to work, and the supply of it is limited.

201. *Iron Battery.* — Instead of platinum, iron may be used with an equally good result in Grove's battery. Care must be taken that the nitric acid does not become dilute, for in dilute nitric acid the iron is violently attacked. In the electro-chemical table, iron stands much inferior to platinum as an electro-negative metal. Its use in the iron battery depends on its becoming highly electro-negative in concentrated nitric acid, or assuming, as it is called, a passive condition. The *passivity of iron* can be produced in various ways. It becomes so when dipped in concentrated nitric acid, when heated in air or oxygen till it changes colour, or when it forms the + pole in the decomposition of water, where ozonised oxygen acts on it. Passive iron suffers no change in dilute nitric acid, which powerfully corrodes active or ordinary iron. The passivity of iron is attributed to the formation on its surface of a very thin layer of oxide, which is insoluble in nitric acid, and electro-negative compared with active iron. Passive iron can be made active by being rubbed with sand-paper, or heated in hydrogen gas. If in the iron battery filled with dilute acid there be any part not passive, that part forms a pair with the passive part, and rapidly dissolves. When the acid is concentrated, however, the surface is kept constantly passive.

Fig. 99.

202. *Bichromate of Potash Cell.*—This cell was discovered by Bunsen. In it the chromic acid derived from the decomposition of bichromate of potash is made use of as an oxidising agent to prevent a deposit of hydrogen on the electro-negative plate, and thus get rid of the counter electro-motive force of

polarisation so detrimental to most forms of one-fluid cell. The cell is represented in section in fig. 100. A globular-shaped vessel of glass, *a*, is taken with a long, wide, cylindrical neck. Two plates of gas-carbon, *c*, *c*, parallel to each other and about an inch apart, are fixed to an ebonite disc, *e*, which closes the mouth of the glass vessel. These plates are in metallic connection with each other, and with the binding screw, A, which is the positive pole. A plate of zinc, *z*, the same width as the carbon plates but only half the length, is attached to a brass rod, *b*, which can be moved up and down in the socket, *s*, and fixed in any desired position by a pinching screw. The socket, *s*, is in metallic connection with the binding screw, which is the negative pole. When in its highest position, the zinc plate is entirely out of the exciting liquid, and the action of the cell is stopped. The liquid consists of a saturated solution (about 4 oz. to a pint) of bichromate of potash in dilute sulphuric acid, and fills only the globular part of the containing vessel.

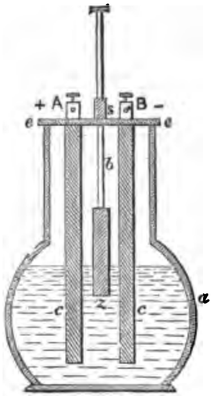


Fig. 100.

The electro-motive force of this cell is great at first, but it rapidly declines when continuously worked through a small external resistance. It rapidly recovers, however, when the cell is out of action; and hence the reason why this cell is so suitable when a pretty powerful current is wanted frequently, but for short periods. It has also the advantage of being entirely free from disagreeable fumes. The chemical action of the cell is represented, according to *Niaudet*, by the equation

$$KO,2CrO + 4SO_3 = Cr_2O_33SO_3 + KO,SO_3 + O_3.$$

203. *Leclanché Cell.*—This is, properly speaking, neither a one-fluid nor a two-fluid cell, but something between the two. It is represented in fig. 101. The electro-positive

element usually consists of a round rod of zinc immersed in a strong solution of sal-ammoniac in water; while the electro-negative element is an ordinary porous cell, in which is placed a long plate of gas-carbon packed round with a mixture of binoxide of manganese and small fragments of gas-carbon. The top of the porous cell is closed by a layer of melted pitch, and the projecting end of the carbon plate is clamped round by a piece of lead to which a binding-screw is attached. The chemical action which goes on is represented by the equation

$$NH_3HCl + 2MnO_2 + Zn = ZnCl + NH_3 + HO + Mn_2O_3.$$

The electro-motive force of this cell is very small, but permanent. By simply taking care to fill up the outside cell occasionally with water, it can be kept for several years always ready for use. It is in consequence much used for

Fig. 101.

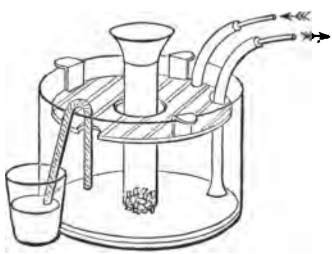


Fig. 102.

working electric bells and railway signals where a weak current for a short time is often required. It is also very suitable for working telephones with microphone transmitters.

204. *Gravitation Batteries.*—These are forms of the two-fluid cell in which the porous cell is altogether dispensed with, the solutions being kept from mixing in consequence

of their difference of density. As an example, we shall describe the cell devised by Sir William Thomson, and which is represented in fig. 102. On the bottom of a wide, shallow, cylindrical glass vessel is placed a circular plate of copper, to which a gutta-percha covered wire is attached. The zinc plate is in the form of a grating, and is supported horizontally by lugs from the edge of the glass vessel at a short distance below its mouth. A glass tube with a funnel-shaped mouth is supported vertically in the centre of the cell, with its lower end just in contact with the copper plate. A glass siphon hangs over the edge of the containing vessel, with the end of its shorter limb midway betweeen the zinc and the copper plates. In charging the cell, a solution of the sulphate of zinc is first poured into the glass vessel till it reaches the zinc plate. Crystals of sulphate of copper are then put into the central tube. These dissolve in the sulphate of zinc solution, and form a solution of greater density, which in consequence spreads over the copper plate. It is evident that, if the cell be kept still, the solutions can only mix by a process of diffusion, and to prevent this as much as possible is the object of the siphon, which is plugged with cotton wick. By capillary action through the cotton, the siphon gradually draws off the sulphate of copper which rises by diffusion, and prevents it from reaching the zinc plate. While the cell is in action, copper is deposited on the copper plate; while SO_4 finds its way to the zinc plate and combines with it. The copper plate, in this way, gradually gets thicker and the zinc plate thinner; while the copper solution becomes less dense by the abstraction of copper from it, and the zinc solution more dense by the addition of zinc to it. The tendency is thus for the solutions to become of the same density, and to get freely mixed. To avoid this, a plentiful supply of crystals of sulphate of copper must be kept in the central tube, and solution of sulphate of zinc must from time to time be gently poured over the zinc plate.

In *Meidinger's* cell, which closely resembles the one just described, the zinc plate is in the form of a ring, which closes the mouth of a glass vessel filled with solution of

sulphate of zinc. At the bottom of the vessel is a shallow glass beaker, which contains a copper ring. The mouth of the beaker is closed by a lid, through the centre of which passes the mouth of an inverted, long-necked, glass balloon. The balloon contains the solution of sulphate of copper, which gradually flows out and spreads over the copper ring.

205. In the following list, the electro-motive forces of the most common cells are given in volts :

		Volts.
Daniell	Sulphuric acid $7\frac{1}{2}$ to 1	1·079
Grove	do.	1·956
Bunsen	do.	1·734
Leclanché	Solution of sal-ammoniac	1·481

206. *Local Action.*—This is a defect to which all forms of cell are subject in which zinc and acid are used. It is caused by want of homogeneity in the zinc plates, which may arise either from actual impurities, such as particles of iron in the zinc, or from the presence here and there of hard and soft parts in the metal. In consequence of these inequalities, one part of the zinc plate is understood to be electro-positive to another, and this, in the presence of dilute acid, sets up a multitude of local circuits, of small electro-motive force but of equally small resistance, which rapidly consume the zinc when the poles are not joined, and which do not contribute in the least to the current when the main circuit is closed. The best remedy for this defect is got by amalgamating the zinc. This is accomplished by first immersing the plates in dilute sulphuric acid, so as thoroughly to clean their surface, and then rubbing mercury over them. In this way the surface assumes a silvery brightness, and becomes so homogeneous in its nature as to preclude local action. If a battery is to be kept in thorough working order, repeated amalgamations of the zinc must be carefully attended to.

CHAPTER XV.

CURRENT RESISTANCE, OHM'S LAW.

207. *Current.*—If a voltaic cell or battery be in proper working order, no chemical action takes place in the cell until the poles be joined by a wire or other conducting connection. If such a cell be carefully insulated, and the potentials of the copper and zinc plates ascertained by a delicate electrometer, it will be found that the potential of the copper plate exceeds that of the zinc plate by a certain quantity. This difference of potential is the electro-motive force of the cell. It is to be noticed that this difference will be exactly the same, even should the cell be bodily charged with a quantity of electricity from an external source, as thereby the potentials of both the copper and zinc plates will be raised by the same amount. If the copper and zinc plates be joined by a wire, in a very short time a steady current will flow in the wire, positive electricity being carried from the copper to the zinc through the wire, and from the zinc to the copper through the liquid. The current thus forms a complete circuit, as may easily be tested by the following experiment. Place the cell so that the copper and zinc plates face north and south, and let the wire joining them go in the same direction. Now hang a small magnetised needle, first a little below the connecting wire, and then a little above the liquid. Observe the deflection, and it will be found to be in the same direction in both positions. A reference to the corkscrew rule already given (sect. 184) will immediately shew that this indicates a current flowing as stated.

208. *Graphic representation of Ohm's Law.*—If the wire connecting the poles of the voltaic cell be examined by means of an electrometer at different points of its length, and the potentials noted, it will be seen that the potential gradually falls as we pass from the positive to the negative pole. This can be represented graphically as follows: Let AB (fig. 103)

represent the wire, supposed to be straight, and let it be homogeneous and all at one temperature, A being the positive and B the negative pole. Let the point A be joined by a fine wire to one pair of quadrants of a quadrant electrometer, the other pair of which is connected with the ground; and let the potential of A thus ascertained be represented by the line AC drawn perpendicular to AB. Similarly let the potential of B be ascertained and represented by the ordinate BZ. Now let any points L and F be taken along the wire, and their potentials ascertained and represented by the ordinates LD and FH. It will be found that the straight line joining C and Z will pass through the points D and H. Thus the slope of the line CZ shews the gradual fall of potential along AB. Now the slope of the line CZ will be greater the greater the difference of height between its ends, and the less the horizontal distance between them—that is to say, the slope is represented by the fraction $\frac{CQ}{QZ} = \frac{CQ}{AB}$ $= \tan \theta$, suppose. If $\tan \theta$ is zero, CZ will be horizontal, and no current will flow from A to B; and the greater the value of $\tan \theta$ the stronger will be the current. Hence the current may be represented by $\tan \theta$. Call it C, and we have $C = \tan \theta = \frac{CQ}{AB}$. Now CQ is the difference of potential, that is, the electro-motive force acting between A and B. Denote it by E. Similarly CO, DP, and HG are the electro-motive forces between A and L, L and F, F and B, respectively. Denote them by E_1 E_2 and E_3.

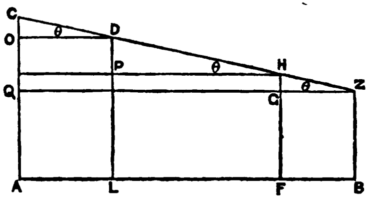


Fig. 103.

Since the wire AB is homogeneous, its total resistance may be represented by its length, and the resistance of any part by the length of that part. Denoting the whole resistance by R,

and the resistances of the parts AL, LF, and FB by R_1 R_2 R_3 we have, from the figure, the following equations:

$$\tan\theta = C = \frac{E}{R} = \frac{E_1}{R_1} = \frac{E_2}{R_2} = \frac{E_3}{R_3}.$$

Putting these into another form we get

$$E = CR, E_1 = CR_1, E_2 = CR_2, E_3 = CR_3,$$

and stating this in words we get the following expression for Ohm's law:

The electro-motive force acting between the extremities of any part of a circuit is the product of the strength of the current and the resistance of that part of the circuit.

The above is to be regarded merely as a graphic representation of Ohm's law. The truth of the law depends upon its perfect accordance with experimental results as far as has yet been ascertained. The law was discovered by Ohm in 1827.

209. *Linear Conductors arranged in Series.*—By a linear conductor is meant one which the current enters and leaves only at two definite points, called the *electrodes.* Such a conductor is represented by a wire perfectly insulated, except at the ends where the current enters and leaves it. When a number of such conductors are connected end to end, so that the current passes through each in succession, they are said to be arranged in *series.* Let AB (fig. 104) represent such a com-

Fig. 104.

pound conductor, consisting, let us suppose, of a length, AC, of copper wire, a length, CD, of iron wire, and a length, DB, of silver wire. Also let E be the total electro-motive force, and R the total resistance between A and B, E_1 and R_1, those between A and C, E_2 and R_2, those between C and D, and E_3 and R_3, those between D and B. It is evident that the same current must pass through each part of the conductor, and Ohm's law applied to the whole and to the several parts gives the equations:

$$E = CR, E_1 = CR_1, E_2 = CR_2, E_3 = CR_3.$$

Adding the last three equations we get

$$E_1 + E_2 + E_3 = C\,(R_1 + R_2 + R_3),$$

but $E = E_1 + E_2 + E_3$.

$$\therefore\ CR = C\,(R_1 + R_2 + R_3), \text{ whence}$$

$$R = R_1 + R_2 + R_3\text{—that is,}$$

the resistance of a series of conductors is the sum of the resistances of the separate conductors.

210. *Linear Conductors arranged in Multiple Arc.*—When a set of conductors is arranged side by side so that one end of each is connected with the point where the current enters, and the other end of each with the point where it leaves the system, they are said to be arranged in *multiple arc.* Such a system is represented in fig. 105. The current denoted, let us suppose, by C, flowing in CA will divide at A, part of it going through each of the conductors, 1, 2, 3. The divided

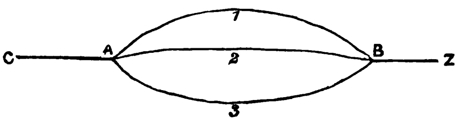


Fig. 105.

current will unite again at B and flow on towards Z. If the resistances of 1, 2, and 3 be all equal, manifestly a third part of the whole current will flow through each of them. Let E be the electro-motive force, and R the resultant resistance between A and B. Also let C_1 be the current, and R_1 the resistance in 1, C_2 and R_2 in 2, C_3 and R_3 in 3. Applying Ohm's law to the system, and observing that the electromotive force between the ends of each conductor is E, we get

$$C = \frac{E}{R},\ C_1 = \frac{E}{R_1},\ C_2 = \frac{E}{R_2},\ C_3 = \frac{E}{R_3}.$$

Adding the last three equations we get

$$C_1 + C_2 + C_3 = E\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right),$$

but $C = C_1 + C_2 + C_3$.

$$\therefore\ \frac{E}{R} = E\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right), \text{ whence}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}.$$

The fraction $\frac{1}{R}$, that is, the reciprocal of the resistance of a conductor is called the *conductivity* of the conductor. Hence we may express the above results as follows :

The conductivity of a multiple conductor is the sum of the conductivities of its separate parts.

211. *Network of Linear Conductors.*—A network of linear conductors is got by taking any number of points and joining every two by a wire. Such a network for five points, involving ten connecting lines, is represented in fig. 106. (The wires are understood not to touch at the point x.) The general problem may be thus stated. Given the quantities of electricity which enter each point of the system in a unit of time, the resistance of each branch, and the internal electromotive force which acts in that branch, it is required to find the difference of potential between each pair of points. Having got this difference, the current in the corresponding branch can be got from Ohm's law. The full investigation of the problem requires the solution of a set of simultaneous equations, and would involve the introduction of too many algebraic symbols to be given here. The general nature of the solution, however, may be stated, and we recommend the actual working out of the problem as a most instructive exercise to the more advanced student. We first observe that there can be no accumulation of electricity at any part of the system, and hence the algebraic sum of all the quantities of electricity which enter it, some being reckoned positive and the rest negative, must be zero. We next notice that the resistance of each branch is the same in whichever direction it is taken, but that the electro-motive forces and currents change sign when their direction is reversed. Then we write down the equations which express the current in each branch in terms of the resistance and the total electro-motive force which acts in that branch. These equations, taken along with the zero relation among the quantities of electricity, give a set of simultaneous equations, involving, as the unknown quantities, the differences of potential between each pair of

points. Solving these equations, we get the difference of potential between each pair of points, from which, knowing the resistance, we find the current in the corresponding branch.

Kirchoff has given the following laws relating to a network of linear conductors:

Law I. At any point of the system the sum of all the currents which flow to that point is zero.

Law II. In any complete circuit formed by the conductors (no matter how many nodes and meshes it may inclose) the sum of the electro-motive forces taken round the circuit is equal to the sum of the products of the current in each conductor multiplied by its resistance.

The first of these laws follows at once from the fact that there can be no accumulation of electricity at any point or node such as A_5, fig. 106, and hence as much electricity must leave the system at that point as enters it. This is simply the law of continuity.

The result stated in the second law may be obtained as follows:

Let us take the closed circuit $A_1\ A_2\ A_3\ A_4$ inclosing the node A_5. Let $P_1\ P_2$ &c. be the potentials at $A_1\ A_2$ &c. Also let C_{12} be the current, and R_{12} the resistance of the branch A_{12}, and so on of the others. Also let E_{12} be the internal electro-motive force in the branch A_1A_2, and so on. These internal electro-motive forces are represented in the figure by the short parallel lines which stand for batteries inserted in the branches. Going round the circuit in the direction $A_1\ A_2\ A_3\ A_4$, and applying Ohm's law to each conductor, we get:

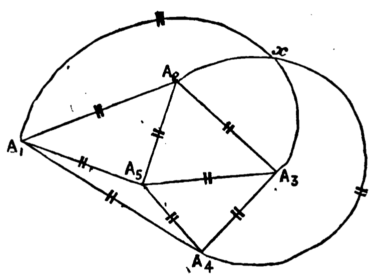


Fig. 106.

$$P_1 - P_2 + E_{12} = C_{12} R_{12},$$
$$P_2 - P_3 + E_{23} = C_{23} R_{23},$$
$$P_3 - P_4 + E_{34} = C_{34} R_{34},$$
$$P_4 - P_1 + E_{41} = C_{41} R_{41}.$$

By simply adding these equations we get

$$E_{12} + E_{23} + E_{34} + E_{41} = C_{12} R_{12} + C_{23} R_{23} + C_{34} R_{34} + C_{41} R_{41},$$

which is the symbolic expression of Kirchoff's second law.

One important result regarding a network of linear conductors remains to be stated. It is this. If an electro-motive force acting in any branch, such as A_1A_2 of the system, causes a certain other electro-motive force, E, to act in another branch, A_4A_5, then the same electro-motive force acting in A_4A_5 will cause an equal electro-motive force, E, to act in A_1A_2. As a particular case of this, suppose an electro-motive force acting in A_1A_2 to cause zero difference of potential between A_4 and A_5, then the same electro-motive force acting in A_4A_5 will cause zero difference of potential between A_1 and A_2. When this last relation obtains between any two branches, these branches are called *conjugate conductors.* An important case of conjugate conductors will be found when we come to the theory of the Wheatstone Bridge.

212. *Specific Resistance.*—If we take a unit cube of a substance and measure its resistance, r, to a current passing parallel to one of its edges, then r is called the *specific resistance* of that substance per *unit of volume.* Suppose we put l of such cubes together so as to form a bar of length l and cross section unity; then we may treat this bar as a set of l conductors arranged in series, and the total resistance will be $R = lr$. Now put s of these bars side by side, forming a compound bar of length l and cross section s, and we may treat the bar as a number of equal conductors arranged in multiple arc. If R be the total resistance, we have

$$R = \frac{lr}{s} \qquad (1).$$

Now it is often very difficult to measure accurately the section of a wire, and in these cases it is better to obtain it

indirectly from its length, mass, and density. Let l be the length, m the mass, and ρ the density of the wire under examination; then since the mass is equal to volume $\times$ density, and volume is equal to length $\times$ section, we have $ls\rho = m$, from which we get $s = \frac{m}{l\rho}$. Substituting this in equation (1), we get $R = \frac{l^2}{m} r\rho$ (2).

By making l and m each equal to unity in this equation, we get $r\rho$ for the resistance of a unit length and unit mass of the substance. Denoting it by r', then r' is called the resistance of the substance per unit of weight. Hence in terms of this unit we have $R = \frac{l^2}{m} r'$. The relation $r\rho = r'$ shews how resistances expressed in terms of the one unit can be got from those expressed in terms of the other. As an example, the resistance of a column of mercury one metre long and weighing one gramme is 13·071 ohms. Dividing this by 13·595, the specific gravity of mercury, we get ·96146 ohms, which is the resistance a column one metre long and one square millimetre in section.

In regard to specific resistance, all bodies may be divided into three great classes. The first class includes all those substances whose chemical constitution is unaltered, both throughout their entire mass and at the electrodes, by the passage of a current through them. This class embraces all metals with their alloys, gas-carbon, and selenium in the crystalline form. The resistance of all bodies of this class, with very few exceptions, increases with a rise of temperature.

The second class includes those substances which are decomposed into two chemical constituents by the passage of the current, the one constituent appearing at the positive, and the other at the negative pole. Such substances are called electrolytes (see Electrolysis, Chap. XVI.). Almost all electrolytes are in the liquid form, with the exception of glass at 100 C., and some other substances near the point of fusion which are found to conduct electrolytically.

The third class includes those substances whose resistance

is so enormous that the strongest electro-motive force can hardly send the feeblest current through them. These substances are called dielectrics. This class includes air and all gases, glass at its normal temperature, paraffin, shell-lac, ebonite, india-rubber, and some oils. We now come to examine a little more in detail these three classes of bodies.

213. *Specific Resistance of Metals.*—An important observation regarding metals was first made by Forbes, who found that metals observed the same order as regards conductivity both for heat and electricity—a result which has been verified recently, and some new facts added by Tait. Another important property of metals is the increase of resistance by the rise of temperature. This can be shewn very easily by an experiment. Include in the circuit of a battery a galvanometer and a length of fine iron wire. Observe the deflection of the needle when it has become steady. Now gradually heat the iron wire by a spirit lamp, and the deflection will be observed to decrease on account of the weakening of the current by the increase of resistance produced by heating the wire. This property of metals has been examined experimentally with great care by Matthiessen, Siemens, and others. It is found that the rise of resistance is very nearly proportional to the increase of temperature from 0° C. to 100° C. Beyond that the increase per degree rise gets gradually less than before. Siemens has given the following empirical formula, which connects the specific resistance with change of temperature from 0° C. to 1000° C.:

$r = \alpha\, T^{\frac{1}{2}} + \beta T + \gamma$ where T is the temperature calculated from absolute zero—that is, from $-273°$ C., and α, β, and γ constants, which depend upon the kind of metal. For copper, $\alpha = \cdot 026577$, $\beta = \cdot 0031443$, and $\gamma = -\cdot 22751$.

Relying on the truth of the above formula, Siemens has constructed a pyrometer for estimating the temperature of a furnace from the change of resistance experienced by a platinum wire placed in the furnace.

Metals generally shew a sudden increase of resistance at the melting-point. After that the increase goes on gradually with rise of temperature, but at a less rate per degree rise than before the melting-point was reached. Bismuth and

antimony are notable exceptions to this rule, as the specific resistance of both exhibit a sudden fall at the melting-point.

The specific resistance of alloys has been found to bear no constant relation to the amount and resistance of the metals of which they are composed. Generally, however, the resistance of an alloy is greater than that of a pure metal. It is important to find that the resistance of some alloys varies very little with change of temperature as compared with pure metals, a fact which has been of much service in the construction of standards of resistance. Such an alloy is got from two parts of gold with one of silver.

Besides heat, several other physical effects produce an alteration in the specific resistance of metals. Putting a wire, for instance, under a state of strain, such as by hanging a heavy weight from it, alters its resistance; and this alteration is more than can be accounted for by the diminution of the section. Sir William Thomson has also noticed that magnetising an iron wire changes its resistance. In the case of crystalline selenium it has been found that light produces a marked effect upon its resistance, and it is now known even that light falling upon selenium can originate a current in it.

214. *Specific Resistance of Electrolytes.*—The determination of the specific resistance of electrolytes is beset with a peculiar kind of difficulty. This arises from the counter-electromotive force of polarisation, which is set up at the surface of contact of the electrolyte with the electrodes. Various methods have been adopted to overcome this difficulty. One is by using what are termed non-polarisable electrodes, such as plates of amalgamated zinc in contact with solution of zinc sulphate. Another is to determine the resistance as far as possible before any great amount of polarisation has had time to take place. This can be accomplished either by using rapidly alternating currents, or by making the surface of the electrodes very large in comparison with the sectional area of the part of the electrolyte whose resistance is being determined.

In all cases the resistance of electrolytes diminishes with a rise of temperature.

Paalzow has examined the resistance of various mixtures

of two different solutions whose individual resistance was known. He finds that the resistance of the mixture is neither the arithmetic nor the geometric mean of the resistances of the two solutions; and also that it does not agree with the result which would be obtained by treating the two solutions as metals connected in multiple arc.

Solutions containing various percentages by weight of the common acids, such as nitric, hydrochloric, sulphuric, &c., have been examined; and likewise similar solutions of the alkalies and alkaline earths, such as chloride of potassium, sal-ammoniac, &c.

In the case of all the acids examined, with the exception of oxalic acid, the resistance is found to have a minimum value corresponding to a certain definite percentage of the acid in the solution. That percentage is 29·7 for nitric, 18·3 for hydrochloric, and 30·4 for sulphuric acid. Sulphuric acid is anomalous inasmuch as it shews two minimum values of the resistance for percentages varying from 0 to 100, the one occurring at 30·4 and the other about 92·5 per cent.

In the case of the alkalies it is found that they can be divided into two great classes—the one class containing those whose solutions *do*, and the other those whose solutions *do not* shew a minimum value of the resistance as the percentage is varied up to the saturation point. Examples of the former class are solutions of chloride of potassium and sal-ammoniac; and of the latter, solutions of common salt, chloride of calcium, and chloride of magnesium.

215. *Specific Resistance of Dielectrics.*—As far as has yet been ascertained, the resistance of all gases and vapours at ordinary pressures and temperatures is practically infinite. Air, for instance, has been found to have a specific resistance which is at least 10^{28} times that of copper; and a similar result has been obtained for steam and the vapours of mercury and sodium. From this it is evident that the gradual loss of electricity which is observed to take place from all charged conductors, however well insulated, cannot be attributed to actual conduction through the air, but must be due either to conduction through the substance or along the surface of the insulating supports.

The resistance of rarefied gases presents some points of importance. It has been shewn by an experiment due to Varley that 323 Daniell's cells were able to produce a current in a tube containing a certain rarefied gas, but that a less number—namely, 304 cells—were able to maintain the current after it had been started. When more cells were added, and the current strength tested by a galvanometer, it was found to be proportional to the excess of the number of cells above 304. That is to say, suppose the current strength for $304+8$, or 312 cells, to be represented by 9, then the current for $304+16$, or 320 cells, would be represented by 18. From this it would appear that the electro-motive force required to maintain a current through a rarefied gas is made up of the sum of two parts, one of which is constant, and the other connected with the current and resistance by Ohm's law.

Numerous experiments have been made to determine the resistance of solid dielectrics such as glass, gutta-percha, india-rubber, &c. With almost no exception the resistance of such bodies diminishes with increase of temperature. This is well shewn in the case of glass, the resistance of which varies from 22,700,000 at 200° C. to 73,500 at 400° C.

Special attention has been given to the determination of the specific resistance of india-rubber and gutta-percha. This has been caused by the extensive use of these substances as insulating coatings for submarine cables. One notable feature has been observed in regard to them—which is, that the resistance varies in a rather uncertain way with time. For instance, in one case the resistance of gutta-percha was observed after the current had flowed, for one minute, for ten minutes, and for nineteen hours; and it was found that the resistance after ten minutes was four times, and the resistance after nineteen hours twenty-three times what it was after one minute.

Subjoined is a table of the specific resistance of a few of the more common substances, where t is the temperature at which the resistance is measured, r the resistance in C.G.S. units, and a the percentage of itself by which r varies per degree C. of rise of temperature.

	t	r	α
Silver (annealed)...........	20°	1521	·37
Copper (annealed)..........	20°	1615	·38
" (hard drawn)	20°	1652	
Platinum (annealed).......	20°	9158	
Iron (annealed).............	20°	9827	
Lead (pressed)...............	20°	19850	·38
German Silver..............	20°	21170	·04
Mercury.......................	20°	96190	·07
H_2SO_4 (max.)...............	18°	$1{\cdot}39 \times 10^9$	1·5
NH_4Cl........................	18°	$2{\cdot}55 \times 10^9$	1·5
$ZnSO_4$ (max.)...............	10°	$26{\cdot}60 \times 10^9$	2·3
H_2SO_4 (pure)...............	18°	$120{\cdot}20 \times 10^9$	4·2
H_2O (pure)..................	18°	135×10^{13}	
Glass..............................	200°	227×10^{14}	
"	400°	735×10^{11}	
Gutta-percha...............	24°	353×10^{21}	
" "	0°	7×10^{24}	

CHAPTER XVI.

MEASUREMENT OF RESISTANCE.

216. *Unit of Resistance.*—The units of resistance first employed were purely arbitrary, and consisted merely of certain lengths of wire of given material, thickness, and density used always at the same temperature. Examples of such arbitrary units are the Étalon of Jacobi, and the still better known Mercury unit of Siemens—the former being the resistance of a copper wire 7·61975 metres long, ·667 millimetres in diameter, and weighing 22·4932 grammes; and the latter the resistance of a column of mercury one metre long, and one square millimetre in cross section, the temperature being 0° C. Many obvious disadvantages attended the use of such arbitrary units, one of the chief of which was that they were not universally adopted; and in consequence the results of one experimenter could not easily be compared with those of another. Hence the necessity

very soon arose for some absolute unit which should be universally used by electricians.

It has already been shewn (sect. 186) that, according to the electro-magnetic system of units, a resistance is a quantity having the same dimensions as a velocity; and hence, the unit of resistance admits of being expressed by a certain definite absolute velocity. Weber, who was the first to suggest such a system of measurement, adopted as his unit a velocity of one millimetre per second; and afterwards, Sir William Thomson, in some researches, employed as his unit a velocity of one foot per second. In 1861, acting upon a suggestion of Thomson, the British Association appointed a committee to investigate thoroughly the entire subject of electrical measurements. In 1864, after much careful experimenting and deliberation, that committee recommended the adoption of a velocity of 10,000,000 metres, or approximately an earth quadrant per second, as the absolute unit of resistance. This unit, called the B. A. unit, or more generally the Ohm, is the one now all but universally used by electricians. Having settled upon the absolute unit, the committee next set about constructing some material representatives of it in the shape of what are known as *unit resistance coils.* Before doing so, however, they had first to determine the resistance, in absolute measure, of a certain coil of wire. This they did essentially by making the coil revolve at a known velocity about a vertical axis, and ascertaining the deflection produced by it upon a magnet delicately suspended at the centre of the coil. As will be fully explained when we come to induction of currents, this deflection is due to a current induced in the revolving coil by the earth's magnetism. Having ascertained the resistance of the coil, it was a comparatively easy task to

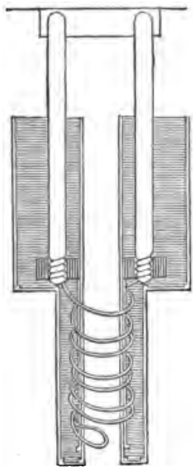


Fig. 107.

construct from it as a basis a coil whose resistance should be equal to one unit or an Ohm. Several such coils were constructed, the wire employed being an alloy of platinum and silver, which was chosen because its resistance was found to vary very little with changes of temperature. The wires, which varied in length from one to two metres, and in diameter from ·5 to ·8 millimetres, were carefully insulated with a double layer of silk, and after being doubled upon themselves were wound upon an elongated brass bobbin as represented in fig. 107. The object of winding the wire double on the bobbin was to insure that at each point of it there should be equal and parallel currents flowing in opposite directions, and so do away with any inductive effect of the one layer of wire upon its neighbour. The wire, after being wound, was carefully imbedded in solid paraffin, its ends being soldered to two stout pieces of copper to serve as electrodes. The whole was then inclosed in a thin casing of sheet-brass to enable it to be immersed in water, and brought to the precise temperature at which the resistance was one Ohm.

217. *Rheostat and Resistance Coils.*—Having got a unit, the next requisite was a series of graduated resistances so arranged that any required resistance could be readily inserted in a voltaic circuit. One of the earliest methods of obtaining a graduated resistance was by means of the *rheostat* invented by Wheatstone. It is shewn in fig. 108. Two cylinders, C′, C, about 6 inches in length, and 1½ inch in diameter, are placed parallel to each other, both being movable round their axes. One of them, C′, is of brass, the other, C, is of well-dried wood. The wooden cylinder has a spiral groove cut into it, making forty turns to the inch, in which groove is placed a fine metallic wire. One end of the wire is fixed to a brass ring, which is seen in the figure at the further end of the wooden cylinder; and its other end is

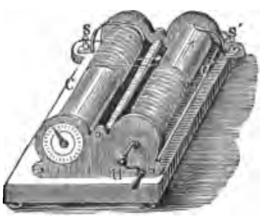


Fig. 108.

attached to the nearer end (not seen in the figure) of the brass cylinder, C′. The brass ring just mentioned is connected with the binding screw, S, by a strong metal spring. The further end of the cylinder C′ has a similar connection with the binding screw, S′. The key, H, fits the projecting staple of either cylinder, and can consequently turn both. As the brass cylinder, C′, is turned in the same direction as the hands of a watch, it uncoils the wire from the wooden cylinder, C′, making it thereby revolve in the same way. When the wooden cylinder is turned contrary to the hands of a watch, the reverse takes place. The number of revolutions is shewn by a scale placed between the two, and the fraction of a revolution is shewn by a pointer moving on the graduated circle, P. When the binding screws, S and S′, are included within a circuit, say S with the +, and S′ with the — pole, the current passes along the wire, on the wooden cylinder, C, till it comes to the point where the wire crosses to the brass cylinder, C′; it then passes up the cylinder C′ to the spring and binding screw, S′. The resistance it encounters within the rheostat is met only in wire, for as soon as it reaches the large cylinder, C′, the resistance it encounters up to S′ may be considered as nothing. When the rheostat is to be used, the whole of the wire is wound on the wooden cylinder, C, and the binding screws are put into the circuit of a constant cell or battery along with a galvanometer. The rheostat is now seldom used unless for rough work, on account of the resistance at the contact of the wire with the metal cylinder being variable and indeterminate.

Resistance coils are definite multiples of the Ohm so arranged that they can be at once included or withdrawn from a voltaic circuit without disturbing the resistance of the other parts of the circuit. They are constructed in a way precisely similar to the unit coil, and are usually attached to the under side of a slab of ebonite as represented in fig. 109. One end of each coil is soldered to massive pieces of brass *a*, *b*, *c*, &c., whose resistance is so small that it may be neglected. Half holes are made in the ends of each of these pieces (C) to admit of conical plugs of brass, *p*, being inserted between them. When a plug is out of the

hole between a and b, suppose, the current passing from A to B has to pass through the corresponding coil; but when it is inserted, the coil is, as it is termed, shunted off, and the

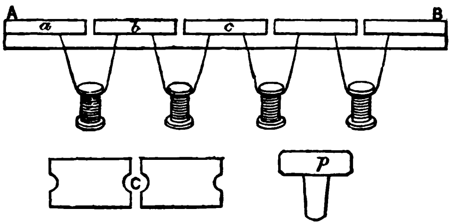


Fig. 109.

current passes without resistance through the brass pieces. It is thus easily seen that the resistance inserted in the circuit between A and B is exactly the resistance unplugged; and to facilitate calculation, the resistance of each coil is engraved upon the corresponding piece of brass. Resistance coils are usually made up in boxes, one of which is represented in fig. 113, and in plan in fig. 114, sect. 221.

218. *Comparison of Resistances.*—The first method of comparing two resistances was by inserting them successively along with a galvanometer into a voltaic circuit, and observing the corresponding currents. In this way the ratio of the resistances was obtained. Thus, let R be resistance of the battery and its connections, E its electro-motive force, and C the current produced by it. Also let r_1 and r_2 be the inserted resistances which are to be compared, and C_1 and C_2 the corresponding currents, then we have by Ohm's law:

$$E = CR = C_1 (R + r_1) = C_2 (R + r_2).$$

From these we get:

$$(C - C_1) R = C_1 r_1$$
$$(C - C_2) R = C_2 r_2$$
$$\therefore O = C_1 (C - C_2) r_1 - C_2 (C - C_1) r_2$$
$$\therefore \frac{r_1}{r_2} = \frac{C_2 (C - C_1)}{C_1 (C - C_2)}.$$

From this we get the ratio of the two resistances provided we can measure the currents C, C_1, and C_2. It is to be observed, however, that this supposes the electro-motive force and resistance of the battery to remain constant during the experiment, a thing which we cannot assume, and which is practically found not to be the case. Hence this method is very defective, and is now never employed for accurate work. Fortunately, however, we have two methods for comparing resistances, both entirely independent of the electro-motive force and resistance of the battery. These are the methods by the differential galvanometer, and Wheatstone's Bridge.

219. *Differential Galvanometer.*—In the differential galvanometer there are two independent circuits made by winding side by side upon the bobbin two well-insulated wires, usually of equal length and thickness. The four terminals are so arranged that currents can be sent in opposite directions through the two coils so as to act in opposite directions upon the suspended needle; and in this way, if the currents are exactly equal, the needle will not be deflected. This is an example of what is called the 'null method' of comparing resistances, seeing that the thing to be observed is the absence of an effect caused by the action of equal and opposite forces.

The general arrangement of the differential galvanometer, as used for comparing resistances, is represented in fig. 110. G is the galvanometer, whose coils are M and N. E is a battery, the current, C, from which divides at F, one part going round M, and the other round N, in the directions EFMH and EFNH respectively. Let m be the deflection produced by a unit current in M, and n that produced by a unit current in N; then, if C_1 and C_2 be the currents in the branches containing M and N, and δ the deflection produced, we have

$$\delta = mC_1 - nC_2 \qquad (1).$$

Now let A be the total resistance in the branch containing M, r the resistance in the branch HF, including that of the battery, and $B + x$ the resistance in the branch containing N, where x is the inserted resistance whose value is to be

compared with a known resistance. Let the resistance A be adjusted till there is zero deflection of the needle. Now let x be removed, and known resistances inserted in its place till

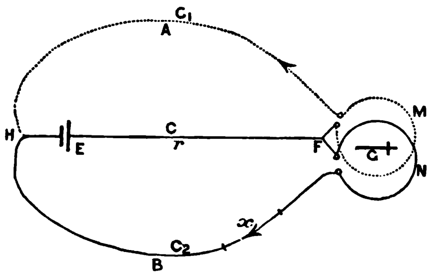


Fig. 110.

there is again zero deflection. If R be the resistance inserted, x will be equal to R, and in this way x is determined in terms of known quantities.

As an instructive example of the use of Ohm's Law, we shall find the equations which give C, C_1, and C_2 in terms of the given quantities.

Looking first at the branch EFMH, we have

$$E = Cr + C_1 A \qquad 2).$$

Looking next at the branch EFBH, we get

$$E = Cr + C_2 (B + x) \qquad (3).$$

Also we have evidently

$$C = C_1 + C_2.$$

Solving these equations, we easily find

$$C = \frac{A + B + x}{D} \cdot E;$$

$$C_1 = \frac{B + x}{D} \cdot E;$$

$$C_2 = \frac{A}{D} \cdot E;$$

where $$D = A (B + x) + r (A + B + x).$$

From (1) we find

$$\gamma = \frac{E}{D}\left\{m(B+x) - nA\right\}.$$

If $\gamma = 0$, then $\qquad m(B+x) = nA.$

Now if R inserted for x makes $\gamma = 0$, then also is

$$m(B+R) = nA,$$

which shews at once that $x = R$.

220. *Wheatstone Bridge.*—This is another example of the null method of comparing resistances. It was first invented by Christie, although brought to perfection by Wheatstone. It consists essentially of a network of six linear conductors, having a battery in one branch and a galvanometer in the branch conjugate to it. The arrangement of the Bridge is shewn in fig. 111.

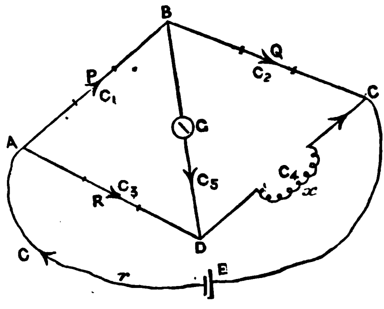


Fig. 111.

E is the battery inserted in the branch CEA, whose resistance is represented by r. The current C from the battery divides at A, part going round ABC, and the other part round ADC. G is a galvanometer inserted in the branch BD, and delicate enough to detect even the feeblest current in that branch. P, Q, and R are resistances, adjustable to any known values, inserted in the branches AB, BC, AD; and x is the unknown resistance, whose value is to be determined, inserted in the branch CD. The remaining parts of the branches are supposed to consist of thick strips of metal whose resistance may be neglected.

In order to find the value of x, the resistances P, Q, and R are so adjusted that no current passes through the galvano-

meter. When this is the case B and D are at the same potential, and from this it follows that the product of the resistances P and x must be equal to the product of Q and R; that is

$$Px = QR, \text{ from which we get } x = \frac{QR}{P}.$$

Hence x is expressed in terms of known resistances.

In order to shew that $Px = QR$, we first observe that the fall of potential from A to C is the same whether we go along ABC or ADC.

Let LH (fig. 112, a), at right angles to LN, represent the

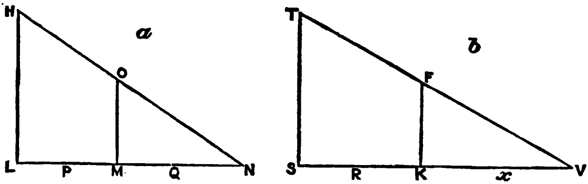


Fig. 112.

difference of potential between A and C. Also let LM and MN represent the resistances P and Q. The fall of the potential along ABC is represented by the slope of the line HN. Hence MO will represent the potential at the point B of the bridge. Again, looking at the path ADC, let ST (fig. 112, b) represent the difference of potential between A and C, and SK and KV the resistances R and x respectively; then the slope of the line TV represents the fall of potential between A and C, and KF the potential at the point D of the bridge. Now, LH is equal to ST, and MO to KF, seeing that B and D are at the same potential. From fig. 112, a, we get

$$\frac{LH}{MO} = \frac{LN}{MN} = \frac{P+Q}{Q} = \frac{P}{Q} + 1.$$

Similarly, from fig. 112, b, we get

$$\frac{ST}{KF} = \frac{SV}{KV} = \frac{R+x}{x} = \frac{R}{x} + 1.$$

But $$\frac{\text{LH}}{\text{MO}} = \frac{\text{ST}}{\text{KF}};$$

Therefore $$\frac{\text{P}}{\text{Q}} + 1 = \frac{\text{R}}{x} + 1.$$

Hence $$\frac{\text{P}}{\text{Q}} = \frac{\text{R}}{x}\text{; that is, P}x = \text{QR.}$$

The equation $\text{P}x = \text{QR}$ can also be proved algebraically by the help of Kirchoff's laws (sect. 211), and as this affords an excellent example of the use of these laws, we shall give the equations from which the result can be obtained.

Let C_1 be the current in AB (fig. 111), C_2 that in BC, C_3 that in AD, C_4 that in DC, and C_5 that in BD; also let C be the current from the battery E, and let G denote the galvanometer resistance.

By Kirchoff's first law, looking at the points A, C, B, and D in succession, we get the equations:

$$C = C_1 + C_3 = C_2 + C_4;$$
$$C_5 = C_1 - C_2 = C_4 - C_3.$$

By Kirchoff's second law, looking first at the circuit ABD and then at the circuit BCD, we get

$$C_1P + C_5G - C_3R = 0;$$
$$C_2Q - C_4x - C_5G = 0.$$

From these equations, by eliminating C_1 C_2 C_3 and C_4, we get

$$C_5 = \frac{Px - QR}{(P + R)(Q + x) + G(P + Q + R + x)}.$$

Hence if the galvanometer shews zero deflection—that is, if $C_5 = 0$—we must have $Px = QR$.

221. *Resistance Box.*—For the practical determination of resistances, a box of resistance coils is usually arranged in the form of a Wheatstone's Bridge. Such a box is represented in fig. 113, and a plan of the top of its lid in fig. 114. The box consists of three parallel rows of coils so connected by stout metal pieces at the ends as to be equivalent to a single long row. The parts AB and BC (fig. 114, *a*) are called the arms of the bridge. Fig. 114, *b*, represents the usual dia-

grammatic form of the bridge; and the letters, in both figures, are made to indicate corresponding parts. The battery is

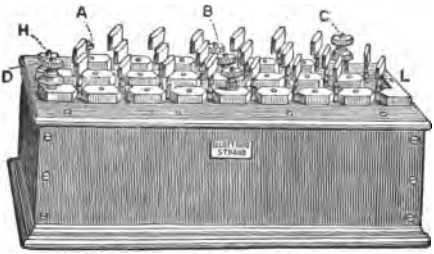


Fig. 113.

usually inserted between A and C, the galvanometer between B and D, and the resistance to be measured

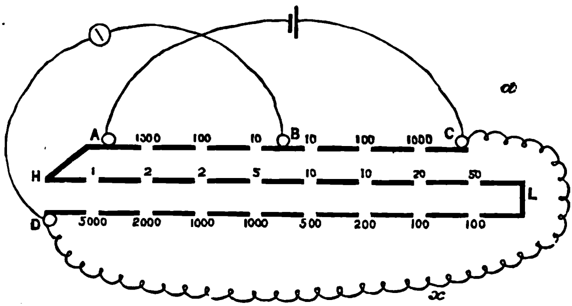
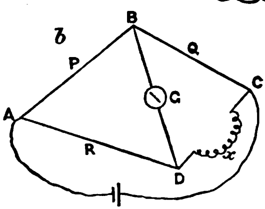


Fig. 114.



between C and D. The resistance unplugged between A and B corresponds to P, that between B and C to Q, and that in the circuit HLD to R. The equation $Px = QR$ gives at once the value of $x = \frac{QR}{P}$. For instance, let the resistances unplugged in AB and BC respectively be 100 and 10, and

suppose in order to produce zero deflection in the galvanometer it is found necessary to unplug 5, 10, and 50 in HLD; then we have $100x = 10\ (5 + 10 + 50) = 650$, which gives $x = 6{\cdot}5$. In order to make the sensibility of the arrangement as great as possible, it is best to make the resistances in the arms equal and as near to the resistance to be measured as possible. It will be observed that the numbers in HLD are so arranged as to give any resistance up to 10,000 Ohms by taking out the proper plugs.

222. *Arrangement of Cells.*—According to Ohm's law, the current obtained from any particular cell is equal to the quotient which results from dividing the electro-motive force by the total resistance. This resistance arises from two sources; the first being the resistance within the cell offered by the exciting liquid, and the second the external resistance. If e represent the electro-motive force; l, the resistance within the cell; w, the external resistance; and C, the strength of the current, or the quantity of electricity actually transmitted, the statement of the law for one couple stands thus: $C = \frac{e}{l + w}$. If we increase the number of cells to n, we increase the electro-motive force n times, and at the same time we increase the liquid resistance n times, for the current has n times as much of it to travel, then $C = \frac{ne}{nl + w}$. If w be small compared with nl—that is, if the external connection be made by a short thick wire—it may be neglected, and so $C = \frac{ne}{nl} = \frac{e}{l}$. This shews that one cell gives in these circumstances as powerful a current as a large battery, and that the increased electro-motive force is expended in pushing the current through the liquid in each cell. But if nl be small with respect to w—as in the external circuit of an electric telegraph battery—nl may be neglected, and $C = \frac{ne}{w}$. Here we learn that the strength of the current increases directly as the number of cells. We may learn from the same that the introduction of the coil of long thin wire of a galvanometer into such a circuit, introducing but a

comparatively small increase of resistance, causes a very slight diminution of the current strength. If, again, we increase the size of the plates of a cell n times, the section of the liquid is proportionately increased, so that whilst the electromotive force remains the same, the internal resistance diminishes n times; therefore $C = \frac{e}{\frac{l}{n} + w}$ or $C = \frac{ne}{l + nw}$. If the external resistance is small, nw may be neglected, and $C = \frac{ne}{l}$, and the strength is thus shewn to increase n times.

223. Suppose now that we have nine cells similar to the one just discussed, the internal resistance of each being ·2, the electro-motive force 16, and the external resistance 15. Let us also, for the sake of simplicity, suppose that they are exactly equal, and that results come out exactly in accordance with Ohm's law. Practically, this never takes place, but the discrepancies can be easily accounted for, as they originate in the apparatus, or faults of observation, and not in the law. Practical results, however, are so near the law as to leave no doubt of its truth. Let us ascertain how these nine cells would act when differently put up. One cell, when $w = 0$, gives a current $C = \frac{16}{15 \cdot 2} = 1 \cdot 05$. Let us now put up the nine cells in succession, as in fig. 115. Here the

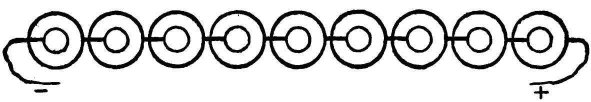


Fig. 115.

electro-motive force of the whole battery is nine times that of one cell, or 144, and the resistance of the whole is also increased nine-fold, or $9 \times \cdot 2 = 1 \cdot 8$, as the current has in the compound circuit to traverse nine times the amount of liquid it has in one. Thus, $C = \frac{144}{1 \cdot 8 + 15} = 8 \cdot 6$, more than eight, and nearly nine times the current that one cell can transmit. Instead of the arrangement in series just investigated, let us

have an arrangement of the cells side by side, as in fig. 116. The electro-motive force is not increased, but the resistance

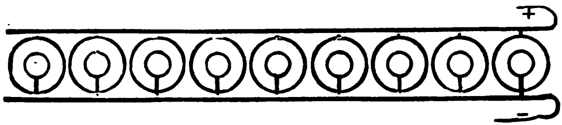


Fig. 116.

is nine times diminished, seeing that the whole acts as one cell of nine times the surface. Here $C = \dfrac{16}{\frac{\cdot 2}{9} + 15} = 1{\cdot}06$, very little more than that given by one cell. Again, put up the nine cells as shewn in fig. 117, where we have three batteries of three cells each, each joining to form one current, the whole acting as one battery, with the plates three times enlarged. $C = \dfrac{48}{\frac{\cdot 2}{3} + 15} = 3{\cdot}1$, or about three times the current of one cell. Before a large resistance, the surface is best employed by being cut up into small cells, arranged successively, than by having a few large cells. Before a small resistance the reverse holds. *The maximum effect is got when the total internal resistance within the battery is equal to the external resistance.* This, of course, is only practicable when the external resistance is less than the resistance of all the cells put together.

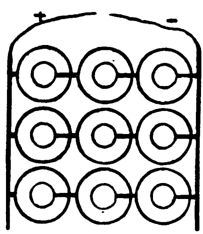


Fig. 117.

When continuous work has to be done by a battery, the size of the plates or cells must not be too small, as small cells containing little zinc and acid soon become exhausted. Large cells do not before great resistance give a stronger current than small cells, but they continue in action for a much longer time.

224. When cells differing both in electro-motive force and internal resistance are put up successively, we have to add all the electro-motive forces for the electro-motive force, and all the resistances for the resistance of the battery. Thus, if we had six cells with the electro-motive forces 9, 8, 7, 10, 6, 12, and the resistances $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{3}$, $\frac{1}{6}$, $\frac{5}{12}$, respectively, the total electro-motive force would be 52, and the total resistance 2, and we should have the formula $C = \frac{52}{2 + w}$. If the last two happened to be reversed and acted in the contrary way, the formula would be $C = \frac{34 - 18}{2 + w}$, the total internal resistance being the same as before.

CHAPTER XVII.

THE PHYSIOLOGICAL, HEATING, LUMINOUS, AND ELECTROLYTIC EFFECTS OF THE GALVANIC CURRENT.

These are developed by the current in its path.

225. The *physiological effects*, as shewn by the convulsions of Galvani's frog preparation, were the first observed manifestation of the current. Fig. 118 shews how these convulsions are obtained. The legs of a recently killed frog are skinned, and the crural nerve laid bare. A zinc wire, BA, holds up the nerve at B, and a copper wire, EA, is made to touch the legs at E and D. Each time that the zinc and the copper wire are made to join at A, the limbs are convulsed, and the contraction of the muscle throws the legs out to the position *f f*. Frog-limbs, as prepared by Galvani, when included in a circuit, form a galvanoscope of excessive sensibility. There is one peculiarity in their action which deserves to be noted. The limbs contract only when

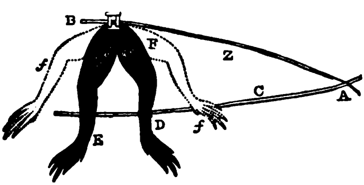


Fig. 118.

the circuit is closed and opened, and remain undisturbed so long as the current passes steadily through them. The more frequently, therefore, the current is stopped and renewed, the greater is the physiological effect. The same is experienced when a current is passed through the human body. When the terminal wires of a battery are lifted one by each hand, except it consist of a very large number of cells, almost the only sensation felt is a slight shock on completing and breaking the circuit. Du Bois Reymond, the great authority on animal electricity, states that the nerves of motion are affected only by changes in the current, whereas the nerves of sensation, so far as they are affected, are affected not only by these, but also by the steady continuance of the current; and that the excitation of the nerves dependent on the changes of the current increases with their frequency and suddenness. Frictional electricity in this way owes its superior physiological power to the instantaneous nature of its discharge. It is only currents of great tension which can be felt by the living subject. The poles of a battery of fifty Bunsen cells, capable of giving a brilliant electric light, for instance, may be handled without much inconvenience. This may be attributed partly to the non-conducting nature of the skin. If the current enter the body by a cut or wound, the sensation is affected even when the current is weak. The physiological effect is also much heightened by moistening the hands with salt and water, or by holding metal handles instead of wires, so as to improve the conducting connection. Another cause of this insensibility may be attributed to the fact that the current is not restricted, as it is in part of the frog preparation, to the nerve, but passes through all the conductors of the system. The nerves of the palate and of sight can be affected by a very feeble current; those of hearing by a battery of some thirty cells. If two strips of silver and zinc be placed the one above, the other below the tongue, and be made to touch, a peculiar taste is experienced; when the strips are placed between the gums and the cheeks, and joined, a flash of light accompanies each junction. Again, when the poles of a battery of thirty cells are inserted into the ears, a continuous noise is heard.

226. *Heating Effects.*—When a current passes through a conductor without performing any work either in the circuit or external to it, its energy is entirely converted into heat. Now if E be the electro-motive force and Q the quantity of electricity which passes, the energy is equal to the product EQ. If H be the quantity of heat—that is, the number of thermal units produced—and if J represent the mechanical equivalent of one thermal unit, the energy is also equal to the product JH. Hence we have the equation,

$$JH = EQ \qquad (1).$$

But by Ohm's law $E = CR$, and since the quantity of electricity which passes is equal to the product of the current strength and the time during which it flows,

$$Q = Ct.$$

Therefore by substituting in (1) we get

$$JH = EQ = CR \cdot Ct = C^2Rt.$$

Therefore $H = \dfrac{C^2Rt}{J}$.

From this we see that the heat developed in any conducting wire by an electric current is proportional to the square of the current strength and to the resistance.

The heat produced by a current can be shewn by passing a strong current through fine wires, when heat is produced sufficient to bring them to a white heat and fuse them. Experiments on the heating effects of the current can be made by an apparatus such as that sketched in fig. 119. B is a bottle filled with alcohol (which is non-conducting), and closed with a cork. The thick wires, *n*, *p*, passing through the cork, are connected with the poles of a battery, and within the bottle they are joined with a thin spiral wire, *www*; *t* is a delicate thermometer. When the circuit is closed, the heat developed in the wire is communicated to the alcohol, the temperature of which is shewn by the thermometer. According to the law stated above, the heating

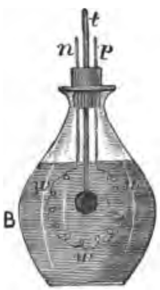


Fig. 119.

effect depends on the strength of the current and the resistance.

A very pretty illustration of the fact that the heat developed is proportional to the resistance encountered, is offered by a chain, the alternate links of which are made of silver and platinum. When a current of sufficient strength passes through the chain, the silver links remain black while the platinum links become red-hot.

The application of the heating powers of the current to igniting gunpowder in mining, &c., is detailed in the Practical Applications of Current Electricity.

227. *Galvanic Spark.*—When the wires connected with a powerful galvanic battery are brought together, no current passes except they are made to touch, or nearly so. On the separation, a brilliant spark takes place, due, as we shall afterwards find, to induction. According to Sir William Thomson, a battery of 5000 Daniell's cells could not originate a spark, if its poles were placed $\frac{1}{20}$th of an inch apart. In Gassiot's water battery of 3520 well-insulated cells, a spark passed when the poles were brought to ·02 of an inch, and continued to do so uninterruptedly for weeks and months together. When the galvanic spark is examined with a microscope, it is found that the light only appears at the − pole. The electric light, the most splendid exhibition of the lighting and heating power of the current, will be described under Practical Applications.

Electrolysis.

228. *Electrolysis* is the term used by Faraday to designate that branch of Voltaic Electricity which treats of the laws and conditions of electro-chemical decomposition. As this decomposition is generally attended by electro-chemical combination, it is sometimes difficult to distinguish electrolysis from the more general subject of *Electro-chemistry*, which embraces all chemical changes resulting in or from the galvanic current. Electrolysis is generally understood to treat of the changes effected in a substance subjected to, but not giving rise to the current.

Faraday's Nomenclature.—A substance capable of decom-

position by the current is called an *electrolyte* (something unbound by electricity). The poles—namely, the wires, plates, or the like—by which the current enters and leaves the electrolyte are called *electrodes* (electric ways, from *hodos*, a way), the + pole being called the *anode* (*ana*, up, and *hodos*), and the – pole the *cathode* (*cata*, down, and *hodos*). The constituents into which the electrolyte is decomposed are called *ions* (from *ion*, going); the electro-positive substances, or those going to the cathode, are called *cations;* and the electro-negative substances which go to the anode are called *anions.* The *electro-chemical equivalent* of an ion is the quantity of it set free by the passage of a unit quantity of electricity. To *electrolyse* signifies to decompose by electric agency.

General Character of Electrolytes.—No substance is decomposed by the current so long as it is in a solid or gaseous state, and it must first be brought to a *liquid state*, either by solution or fusion, before the current acts on it. There are some unimportant exceptions to this. The passage of electricity through compound gases in a state of great rarity, as in the so-called vacuum tubes, frequently separates them up into their constituents. The electric spark in air effects the combination of oxygen with nitrogen; nitric acid being produced. Electrolytes must be *chemical combinations*, as these only can be decomposed. Metallic alloys, when fused, though they conduct the current, are not decomposed by it.

229. *Faraday's Law.—Electrolytes are resolved under the action of the current into anions and cations, which appear at their respective electrodes in the proportion of their atomic weights.* The action of the current on one or two substances will best illustrate the meaning of this law.

Electrolytes.	Composition.	+ Cations.	– Anions.	Relative Proportions.
Hydrochloric Acid..........	HCl	H	Cl	1 to 35·5
Chloride of Sodium........	$NaCl$	Na	Cl	23 to 35·5
Sulphuric Acid.............	H_2,SO_4	H_2	SO_4	2 to 96
Sulphate of Sodium........	Na_2,SO_4	Na_2	SO_4	46 to 96
Sulphate of Ammonium...	$(H_4N)_2,SO_4$	$(H_4N)_2$	SO_4	36 to 96
Water........................	H_2O	H_2	O	2 to 16

Thus common salt (NaCl) is composed of a simple cation, Na, whose atomic weight is 23, and of a simple anion, Cl, whose atomic weight is 35·5. Sulphate of ammonium is composed of two atoms of ammonium $(H_4N)_2$ as a complex cation, and one atom of sulphion (SO_4) as a complex anion. The atomic weight of ammonium (H_4N) is 18, and of sulphion (SO_4) 96. It will be thus seen that chemical formulæ give the electrical as well as chemical composition of electrolytes. In acids, hydrogen forms the cation, and the acid radicle, the other constituent, the anion. In the salts of an acid, the metal that takes the place of hydrogen in the acid is the cation of the salt, and the other constituent, the salt radicle, is, as in the acid, the anion.

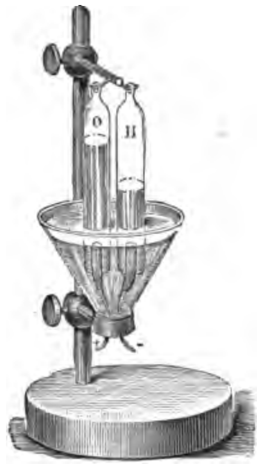


Fig. 120.

The decomposition of water by platinum plates is always taken as the best visible illustration of electrolytic action. Fig. 120 represents a very convenient apparatus for the purpose. A glass basin is made so as to admit a cork below, through which two wires pass having slips of platinum plate soldered to them above. Two glass tubes, open below, are hung over the plates, to hooks projecting from an upright support. The bowl is filled with acidulated water; and the tubes, after being filled with the same, are inverted, and hung with their lower ends inclosing the plates. When the wires projecting downwards from the cork are connected with the poles of the battery, hydrogen rises from the –, and oxygen from the + electrode, to fill each its separate tube. As the decomposition proceeds, twice as much hydrogen is liberated as oxygen. When the tubes are filled, they may be removed and examined.

Hydrogen is here the type of the metals, or other electro-

positive substances, disengaged at the − pole, and oxygen of the acid and salt radicles, or other electro-negative substances, set free at the + pole. Moreover, the proportions of the volumes of the two gases being that of their chemical combining volumes, reminds us that, when a body is decomposed, its components are always separated in the proportions in which they were united, namely, those of their atomic weights. If the tubes of this apparatus be graduated, it will be seen that the volume of hydrogen produced is always double the volume of oxygen produced in the same time. Platinum plates are here employed because platinum does not enter into combination with either of the gases, so that both are disengaged. The oxygen got by this process smells strongly of ozone. This shews that the gas, when electrically set free, possesses more than usual chemical activity, a characteristic common to the products of electric decomposition. They are set free in what is called their *nascent state*, in which they form combinations with other substances with more than usual readiness.

230. *Voltameter*.—This was invented by Faraday for testing the strength of a current. Fig. 121 shews how it may be

Fig. 121.

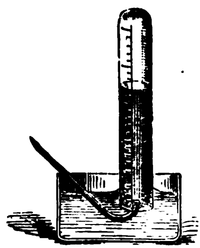


Fig. 122.

constructed. Two platinum plates, each about half a square inch in size, are placed in a bottle containing water acidulated with sulphuric acid; the plates are soldered to wires which pass up through the cork of the bottle; binding screws are attached to the upper ends of these wires; a glass tube fixed into the cork

serves to discharge the gas formed within. When the binding screws are connected with the poles of a battery, the water in the bottle begins to be decomposed, and hydrogen and oxygen rise to the surface. If, now, the outer end of the discharging tube be placed in a trough of mercury (mercury does not dissolve the gases), and a graduated tube (fig. 122), likewise filled with mercury, be placed over it, the mixed gases rise into the tube, and *the quantity of gas given off in a given time measures the strength of the current.* The unit current may be taken as one which is capable of giving off one cubic centimetre of gas per minute. The voltameter chooses as a test the work which the current can actually perform, and establishes a uniform standard of comparison. The plates of the voltameter must be small, for when they are large, a small quantity of electricity is found to pass without decomposing the water. It is found, also, that a minute quantity of the oxygen forms peroxide of hydrogen (H_2O_2) with the water, and remains in solution, so that when very great accuracy is required the hydrogen alone ought to be measured.

Secondary Action.—When sulphate of copper is decomposed by two copper electrodes, copper is deposited at the − pole, and SO_4 enters into combination with the copper of the + pole, and neither oxygen nor hydrogen is disengaged. When platinum electrodes are used, copper is deposited at the one and oxygen is disengaged at the other. The reason is this: SO_4 does not enter into combination with platinum, and when set free acts on the water in which the salt is dissolved, forming oxygen and sulphuric acid. Thus, $SO_4 + H_2O = H_2,SO_4 + O$. The liberation of the oxygen thus arises from a purely chemical action, subsequent to electrolytic action. This is called *Secondary Action,* which denotes, as here, the action of the liberated ions upon the constituents of the solvent or substances present in it. Secondary action is well shewn by the apparatus that Daniell employed for the electrolysis of salts. This consisted of a voltameter in which the gases were collected separately, having a porous diaphragm dividing it into two compartments. When such an apparatus is filled with a solution, say of sulphate of sodium, and subjected to

the current, oxygen and hydrogen are set free, as they would be in a voltameter like the one described in fig. 120. At the same time soda is formed in the cathode compartment and sulphuric acid in the other. The current thus seems to do double work; it appears at the same time to decompose water and the sulphate of sodium. This double action must be attributed to secondary action. Sulphate of sodium, Na_2SO_4, is decomposed into the cation Na_2 and the anion SO_4. Na_2, in the presence of water, becomes soda, Na_2O, and liberates hydrogen, thus, $Na_2 + H_2O = Na_2O + H_2$; and SO_4, acting also on the water, becomes, as already shewn, sulphuric acid and oxygen. Thus the separation of the constituents of the salt is due to electric action, and the liberation of oxygen and hydrogen to a secondary chemical action. *The decomposition of water*, in an ordinary voltameter, *is very probably due to secondary, not primary action.* If it be charged with pure water, little or no decomposition is effected, even when the battery consists of 30 or 40 cells. On the addition of a few drops of oil of vitriol, the gases are disengaged in abundance. It is thus, probably, the sulphuric acid that is decomposed in the first instance, and the water in the second. Electrolytic action splits up H_2SO_4 into H_2 at the $-$ pole, and SO_4 at the $+$ pole; the former is freed, the latter acting on the water becomes sulphuric acid again, and liberates oxygen in the way just shewn. No sulphuric acid is lost in the operation, but it is constantly unformed and reformed. It is considered by many authorities that water never yields directly to the current—that it is not, in fact, an electrolyte. With the exception of the case of fused chlorides, and when one of the poles is eaten away, and the other receives a metallic deposit, electrolysis is almost always accompanied by secondary action, it being frequently a matter of difficulty to unravel the primary from the secondary action in the results.

When there are several electrolytes in one decomposing cell, all are more or less acted upon when the current is strong; but when it is weak, the action is confined to the best conductor, or to the one yielding most readily to the current. Water, the usual solvent, is never decomposed directly when it holds

an electrolytic salt in solution, the action being expended exclusively on the salt.

231. *When there are several electrolytes each in distinct cells in the same circuit.*—If, instead of one voltameter included in the circuit, we have several, we find that, whatever amount of gas is liberated in one of these, the same amount is liberated in all, and that independent of the size of the plates and amount of acid in each. We learn, therefore, that the chemical power of the current is the same at every point of the circuit where it is manifested. Suppose, instead of two or three voltameters in the circuit, we have one or two decomposing cells of the following description. A test tube, having a platinum wire, on which the glass has been fused, passing through the bottom, is partially filled with protochloride of tin, which is kept fused by the heat of a spirit-lamp. The platinum wire at the bottom of the tube forms one electrode, and one descending from the top forms the other, dipping below the fused chloride. If, then, this cell be included in the circuit along with the voltameter, and a similar cell containing fused chloride of lead, so that the current enters the tubes by the upper electrodes, and leaves by the lower, the water, protochloride of tin, and chloride of lead are decomposed simultaneously by the current passing through each. In the voltameter, hydrogen and oxygen are disengaged; in the tubes, metallic tin is deposited at the lower electrode of the one, and lead at the other; whilst chlorine is liberated at the upper electrodes of both. If, now, the quantity of hydrogen, tin, and lead thus set free be weighed, it will be found that their weights are in the proportion of their chemical equivalents—namely, as 1 to 59 to 103. From such experiments as these, Faraday concluded that *when the current passes through a series of binary electrolytes, consisting of one equivalent of each of the elementary bodies, the quantities of the separated elements of the electrolytes are in the same proportion as their chemical equivalents.* It is not only in cells exterior to the battery that this law holds, but in the cells of the battery itself. If the battery which effected the above decomposition consisted of six cells, for each equivalent of hydrogen, tin, and lead separated without the

battery, one equivalent of zinc (=32) in each cell would have been dissolved, and an equivalent of hydrogen disengaged at each of the copper plates, if the cells were one-fluid. Hence, also, if in any circumstances one cell of say Bunsen's battery gives a current as strong as two cells of a one-fluid arrangement, the Bunsen cell would consume but half the zinc consumed in the other. Hence the economy of cells of great electro-motive force.

Faraday's law holds also for binary compounds whose elements do not stand in the relation of an equivalent of the one to an equivalent of the other, but with this modification, that the weights of the *electro-negative elements* alone, separated in the action, are in the ratio of their equivalents. Thus, if the same current pass through two decomposing cells, one containing a solution of the subchloride of copper ($CuCl$), consisting of an equivalent of copper and half an equivalent of chlorine, and the other of the chloride of copper ($CuCl_2$), consisting of an equivalent of each, the same quantity of chlorine will be disengaged in both, but twice as much copper is deposited in the first as in the second. Had there been a compound of copper with the formula ($CuCl_3$) containing an equivalent and a half of chlorine capable of decomposition, we should expect in the same way that for one equivalent of chlorine disengaged there would be $\frac{2}{3}$ds of an equivalent of copper. Becquerel, from such instances, expresses Faraday's law somewhat to this effect: *When the same current passes through a series of electrolytes, the weights of the separated anions are to each other as their chemical equivalents.* The anions here mentioned may be either simple or complex, although the law at first had reference only to elementary substances. Thus, if one cell contained tribasic phosphate of sodium (Na_3PO_4) in solution, and the other chloride of sodium ($NaCl$), one atom of PO_4 being equivalent to three of Cl, then for every atom of PO_4 set free in the one cell, three atoms of Cl would be disengaged in the other. The atomic weight of PO_4 is 95, of 3Cl 3 times 35·5—namely, 106·5. The cations and anions are disengaged in each cell according to the law (sect. 229).

The amount of decomposition effected by the current is in

proportion to the current strength.—This law has been already assumed in the discussion of the voltameter (sect. 230). The accuracy of this law is somewhat compromised by the fact that liquids possess, to a certain extent, the power of conducting electricity without electrolytic action, so that all that passes in this way is chemically lost. Fortunately, the error thus introduced is very small, and can be therefore practically disregarded.

Electro-metallurgy.—The application of electrolysis to the arts will be found in the chapter on Practical Applications.

CHAPTER XVIII.

CONTACT FORCE AND THERMO-ELECTRICITY.

232. *Contact Force.*—When any two substances are placed in contact there must always be a definite surface of separation between them. It is found that, in almost all cases, an electro-motive force acts across this surface at right angles to it, producing electrical displacement, and making the one substance assume a higher potential than the other. This electro-motive force has received the name of *Contact Force;* and if A be the potential of the one substance, and B that of the other, A being the higher, the contact force is represented by the symbol $A \mid B$, where it is understood that $A \mid B = -B \mid A$. The existence of contact force, in the case of metals, was first clearly pointed out by Volta by an experiment such as the following:

Suppose we take a delicate condensing electroscope whose lower plate consists of a circular disc of zinc to which a pair of gold leaves is attached, and its upper plate of a similar disc of copper to which an insulating handle is attached. Let the one disc be put on the top of the other with a thin layer of shell-lac varnish between them. In this position let a copper wire be bent round so as to touch simultaneously the upper surface of the copper disc and the lower surface of the zinc. Now remove the copper wire, and raise the copper

disc by its insulating handle, when the gold leaves will be seen to diverge with positive electricity. The explanation of this experiment is as follows: The contact of the copper wire with the zinc plate produces a definite difference of potential between them, which we may represent by V, and if the copper plate be put in connection with the earth, V will be the potential of the zinc plate. Now when the copper plate is raised, the capacity of the zinc plate is diminished, and its potential V increased in the same proportion. Hence the divergence of the gold leaves.

It is to be borne in mind, however, that in this experiment we have other contacts besides that of zinc and copper, namely, the contacts of air with zinc, and air with copper; and experiment has not yet clearly shewn what part these contacts play in producing the effect.

In studying contact force it may be conveniently divided into three kinds: (1) Contact force of metals with metals; (2) Contact force of metals with fluids; (3) Contact force of fluids.

233. *Contact Force of Metals—Volta's Law.*—Volta found that, when any number of metals are joined together in series, the sum of the contact forces between the intermediate metals is equal to the contact force between the two end ones. Thus if A, B, C, D be four metals joined end to end, we have $A \mid B + B \mid C + C \mid D = A \mid D$, which equation can be put into the other two forms:

$$A \mid B + B \mid C + C \mid D - A \mid D = 0, \text{ and}$$
$$A \mid B + B \mid C + C \mid D + D \mid A = 0.$$

From the last equation we see that there is no resultant electro-motive force when the metals are joined up so as to make a complete circuit; and this is exactly what we should expect, as otherwise it would be possible to obtain a current which would produce heat in the circuit, and could be made to do mechanical work without any expenditure of energy, which is of course impossible. It is to be understood, however, that all the junctions must be at the same temperature.

Two remarkable illustrations of the contact force between metals have been given by Sir William Thomson. In the

one experiment he took a flat circular ring consisting, the one half of zinc and the other of copper soldered together along a line which formed a diameter of the ring. A light flat aluminium index with a counterpoise weight was suspended above the ring and close to it by a silk fibre, so as to turn about an axis perpendicular to the plane of the ring and passing through its centre. The index was so adjusted as to hang, when in equilibrium, along the line of junction of the two metals. When the index was electrified positively, it turned from the zinc towards the copper; and when negatively, from the copper towards the zinc; indicating that the zinc was at a higher potential than the copper in virtue of the contact force at the junction. In the other experiment a cylinder of zinc was suspended vertically from an insulating support. A copper funnel was placed in the upper part of the cylinder so as to have its narrow outlet in the axis of the cylinder and at a point midway between its ends. The funnel was filled with copper filings, which trickled down and were received on an insulated dish in metallic connection with one pair of quadrants of the quadrant electrometer; the other pair of which was connected to earth. The electrometer indication shewed that the dish was receiving a constantly increasing negative charge. This is explained by the contact force between the copper and zinc rendering the zinc positive and the copper negative. In consequence, each copper filing breaks away with a small negative charge which is increased by the induction between itself and the zinc cylinder, and which it gives up on falling to the insulated dish. This is an example of an electric machine worked by gravitation, inasmuch as the earth's attraction has to overcome the electrical attraction between the zinc cylinder and each copper filing. The filings in this way fall slower than they would do if there were no electrical effect.

234. *Determination of Contact Force.*—Volta was the first to give values for the contact force of the commoner metals, and although these values are but rough approximations they are still sufficient to illustrate his law. The chemical symbols for the metals being used—Zn for zinc, Pb for lead (Latin *plumbum*), Sn for tin (*stannum*), Fe for iron (*ferrum*),

Cu for copper (*cuprum*), Ag for silver (*argentum*)—the values are as follows:

$$\mathrm{Zn} \mid \mathrm{Pb} = 5, \quad \mathrm{Pb} \mid \mathrm{Sn} = 1, \quad \mathrm{Sn} \mid \mathrm{Fe} = 3, \quad \mathrm{Fe} \mid \mathrm{Cu} = 2,$$
$$\mathrm{Cu} \mid \mathrm{Ag} = 1.$$

By adding these values we find Zn | Ag = 12, which is the value given by Volta. Similarly, by adding the first four values, we find Zn | Cu = 11, and so on of the others.

The contact force of metals has been determined in various ways by several experimenters. As an example, we may take the method adopted by Kohlrausch. Two equal circular discs of the metals to be tested are taken: let us suppose of zinc and platinum. These are fixed to insulating supports so as to be opposite each other with their planes vertical, and strictly parallel. An arrangement is also made whereby the discs can be separated and replaced always in the same position. In performing the experiment, the discs are first placed with a thin layer of air between them. A platinum wire is bent so as to touch simultaneously the two plates, the platinum plate being at the same time put to earth. The plates are now separated, and the zinc put in metallic connection with an electrometer. Let the electrometer indication be a, the contact force between the zinc and platinum is proportional to a, and may be represented by xa. We have then

$$\mathrm{Zn} \mid \mathrm{Pt} = xa. \qquad (1)$$

The plates are next put into the same position as before, but this time they are connected through a Daniell's cell by means of its copper terminals. The plates are again separated as before, and the zinc connected with the electrometer. Let the reading be b. Then we have, if E be the electro-motive force of the Daniell:

$$\mathrm{Zn} \mid \mathrm{Cu} + \mathrm{E} + \mathrm{Cu} \mid \mathrm{Pt} = xb;$$

or, by Volta's law, $\quad \mathrm{Zn} \mid \mathrm{Pt} + \mathrm{E} = xb. \qquad (2)$

Lastly, the plates are again put in position, connected through the cell, but in the reverse way, and separated as before. Let the reading this time be C; then

$$\mathrm{Zn} \mid \mathrm{Pt} - \mathrm{E} = xc. \qquad (3)$$

By adding and subtracting (2) and (3) we get

$$2\text{Zn} \mid \text{Pt} = x\,(b + c),$$

and $$2\text{E} = x\,(b - c).$$

By division we have

$$\frac{\text{Zn} \mid \text{Pt}}{\text{E}} = \frac{b + c}{b - c};$$

that is, $$\text{Zn} \mid \text{Pt} = \frac{b + c}{b - c}\text{E}.$$

Hence the contact force of zinc and platinum is found in terms of the electro-motive force of a Daniell's cell. By this method Kohlrausch found Zn | Cu to be equal to ·48 of a Daniell's cell, a result which agrees closely with the value, half a Daniell, given by Sir William Thomson.

235. *Contact Force between Metals and Liquids.*—Although the contact force between metals and liquids is very small, still its existence has been clearly made out by several investigators. It has been found also that the contact forces between a series of metals and liquids do not obey Volta's law—that is to say, the contact force between the two end substances joined

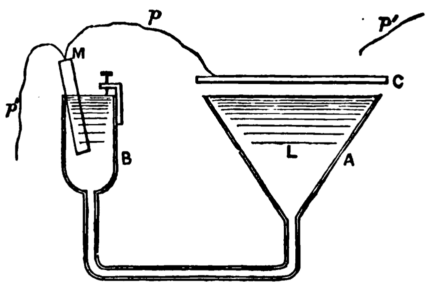


Fig. 123.

directly is not equal to the sum of the contact forces between the intermediate substances when some of these substances are liquids. The following is Hankel's method of determining the contact force between a metal and a liquid: A (fig. 123) is a glass funnel with a narrow tube bent twice at a right

angle, and ending in an enlarged portion, B. A is filled with the liquid to be tested, L, which of course will stand at the same level in B. The metal M to be tested is placed in B. C is a copper disc which can be raised or lowered at pleasure, and can also be fixed at a definite position close to, but not touching, the surface of L, so that the surface of L and the lower surface of C act as the opposed faces of the plates of a condenser.

In performing an experiment, C and M are first connected by a platinum wire p, and M is at the same time put to earth. The wire p is then removed, and C lifted and put in connection with the electrometer. Let the reading be a; then

$$\mathrm{Cu} \mid \mathrm{Pt} + \mathrm{Pt} \mid \mathrm{M} + \mathrm{M} \mid \mathrm{L} = xa;$$

that is,

$$\mathrm{Cu} \mid \mathrm{M} + \mathrm{M} \mid \mathrm{L} = xa. \tag{1}$$

The liquid L is next removed, and a plate of the metal M is placed so that its upper surface is in the same plane as the former surface of the liquid. C is then lowered to its former position, contact is made by p between C and the plate of M, and C raised and connected with the electrometer as before. Let the reading this time be b, then

$$\mathrm{Cu} \mid \mathrm{Pt} + \mathrm{Pt} \mid \mathrm{M} = \mathrm{Cu} \mid \mathrm{M} = xb. \tag{2}$$

Lastly, a zinc plate is put in the place of the plate of M, and the same operations repeated. If the reading be now c, we have

$$\mathrm{Cu} \mid \mathrm{Pt} + \mathrm{Pt} \mid \mathrm{Zn} = \mathrm{Cu} \mid \mathrm{Zn} = xc. \tag{3}$$

From (1) and (2) we have $\mathrm{M} \mid \mathrm{L} = x(a - b)$; and substituting in this the value of x from (3) we get

$$\mathrm{M} \mid \mathrm{L} = \frac{a-b}{c} \mathrm{Cu} \mid \mathrm{Zn}.$$

Thus the contact force between the metal and the liquid is determined in terms of that between copper and zinc.

236. *Contact Force between Two Liquids.*—Although the experiments are somewhat difficult, it has been made out that there is a clear contact force between liquids, and that the contact forces between a series of liquids do not obey Volta's law. The cell of Becquerel is usually given as an

example of such contact force. It consists of a porous jar containing a solution of potash immersed in a vessel filled with nitric acid. Strips of platinum are placed in the potash and nitric acid to serve as electrodes, and the current is found to go outside the cell from the potash to the nitric acid. Several examples of similar cells have been given by Faraday and others.

The contact forces between various liquids have been directly observed by Ayrton and Perry by an elaborate series of experiments conducted in order to ascertain if the resultant electro-motive force in any voltaic arrangement is equal to the sum of the observed electro-motive forces of contact at all the junctions of heterogeneous substances in the circuit. They find this to be the case, to a very close degree of approximation, in all the voltaic arrangements which they tested. A few examples will make their results clear. Let C, Z, L represent the copper, zinc, and liquid of a simple cell; and let L_1 be the liquid in contact with the copper, and L_2 the liquid in contact with the zinc in a Daniell's cell. Then we have for

(1) A simple cell with distilled water:

$$C \mid L + L \mid Z + Z \mid C$$
$$\cdot 074 + \cdot 126 + \cdot 750 = \cdot 950.$$

Electro-motive force measured directly = ·832 to ·942 increasing slowly.

(2) A simple cell with nearly pure saturated zinc sulphate solution:

$$C \mid L + L \mid Z + Z \mid C$$
$$-\cdot 113 + \cdot 358 + \cdot 750 = \cdot 995.$$

Directly observed E. M. F. = 1·000.

(3) Daniell with distilled water and pure saturated copper sulphate:

$$C \mid L_1 + L_1 \mid L_2 + L_2 \mid Z + Z \mid C$$
$$\cdot 028 + \cdot 071 + \cdot 126 + \cdot 750 = \cdot 975.$$

Directly observed E. M. F. = ·995.

(4) Daniell's cell with pure saturated copper sulphate and nearly pure saturated zinc sulphate:

$$C \mid L_1 + L_1 \mid L_2 + L_2 \mid Z + Z \mid C$$
$$\cdot028 \; - \; \cdot033 \; + \; \cdot358 \; + \; \cdot750 = 1\cdot103.$$

Directly observed E. M. F. = 1·068 to 1·081 increasing slowly.

Thermo-electricity.

237. When a circuit is made of a series of different metals all at one temperature, Volta's law holds good, and the contact forces balance each other so that no current is produced in the circuit. If, however, the junctions be at different temperatures, the contact forces do not balance each other, and a current is produced whose direction and strength depend upon the kind of metals and the temperature of the junctions. Currents so produced—that is, by heating the junction of different substances—were first discovered by Seebeck, and are called *Thermo-electric* currents. Such a current is readily shewn by soldering together a piece of iron and copper wire, and attaching the free ends to the terminals of a galvanometer. On slightly heating the soldered junction, a current will be observed whose direction is from the copper to the iron across the hot junction. Thermo-electric currents are produced not solely by heating the junction of dissimilar metals; they have also been observed by heating the junction of a liquid and a metal, and also the junction of two liquids. Even in a conductor of one metal such a current can be produced, provided the heat be applied at a point where there is some abrupt change in the nature or form of the material, such as from a soft to a hard, from a strained to an unstrained, or from a thick to a thin part of the conductor.

238. *Thermal Currents with Two Metals.*—A current is always obtained when the point of junction of any two metals is heated. The two metals which shew this property in the greatest degree are bismuth and antimony. When a bar of antimony, A (fig. 124), is soldered to a bar of bismuth, B, and their free extremities are con-

nected with a galvanometer, G, on the junction being heated, a current passes from the bismuth to the antimony, as shewn in the figure. When S is chilled by applying ice, or otherwise, a current is also produced, but in the opposite direction. Such a combination constitutes a thermo-electric pair. Applying the same mode of explanation to this pair as to the galvanic pair, we find bismuth is + within and − without the pair, antimony − within and + without the pair. Bismuth thus forms the − pole, but + element; antimony the + pole, but − element of the pair. The metals may be classed in thermo-electric just as they were in electro-chemical order. The following table gives them in this order, the direction of the arrow shewing how the current goes within the pair:

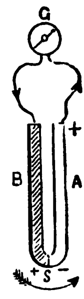


Fig. 124.

Heat.

→

Bismuth,	25
Cobalt,	9
Potassium,	5·5
German Silver,	5·2
Nickel,	5
Sodium,	3
Mercury,	2·5
Aluminium,	1·3
Magnesium,	1·2
Lead,	1·03
Tin,	1
Copper,	1
Platinum,	·7
Silver,	0
Gas Coke,	−·05
Zinc,	−·2
Iron,	−5
Antimony,	−10
Tellurium,	−179

←

Cold.

The order and numbers in this table are those given by Dr Mathiessen. The numbers give the relative electro-motive forces, and are calculated on the scale of copper-silver as unity. The greater the difference between the two numbers, the greater the electro-motive force. When two metals with the same sign are associated, the difference of the numbers gives the electro-motive force of the pair, with different signs the sum. Thus the electro-motive force of a bismuth and antimony pair is $25-(-10)=35$; of bismuth-copper, $25-1=24$;

of iron-antimony, $-5-(-10)=5$. Tellurium, from its rarity, cannot be practically employed. The structure and purity exercise an important influence on the electro-motive force. The numbers of bismuth and antimony in the table are given for those metals when cast. Commercial pressed wire of bismuth would stand as 36, and antimony as -2. Temperature has also an important influence in determining this table. The order and numbers given are for temperatures between 40° and 100° F. For other temperatures, the table would be different for several of the metals.

It will be seen that metals like bismuth and antimony, which have a crystalline structure, are best suited for a thermo-electric pair. It thus resembles a pyro-electric crystal like tourmaline, which, when heated, shews an opposite electricity at each end. If it had a low conducting power like the metals just named, we might expect from it a thermo-electric current instead of mere polarity. It is probable that the crystalline structure, however, accounts for the appearance of electricity in both cases.

239. *Thermo-electric Battery.*—One bismuth-antimony pair has very little power. To increase this, several pairs are associated together, as shewn in fig. 125, where the same tension-arrangement is adopted as in a galvanic battery. The heat in this case must be applied only to one row of soldered faces. The current effect depends on the difference of temperature of the two sides. When a strong current is required, the one series must be kept in ice or in a freezing mixture, whilst the other is exposed to heat radiating from a red-hot plate of iron. As in the voltaic pair, the electro-motive force is proportionate to the number of pairs; the size of the bars, like the size of the plates, merely aiding to diminish the resistance. The electro-motive force of a thermo-electric battery is small; according to Dr Mathiessen, that of 25 bismuth-tellurium pairs equalling one cell of Daniell's battery when the one series is kept at 32° F. and the other at

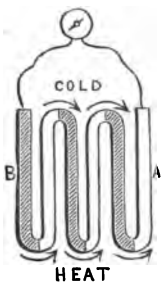


Fig. 125.

212° F. In consequence of the low electro-motive force of the thermo-electric battery, the galvanometer to be used with it must introduce as little resistance as is consistent with the best effect on the needle. Hence special galvanometers are used, in which the coil wire is short (200 turns) and thick ($\frac{1}{25}$ inch); these are called thermo-galvanometers.

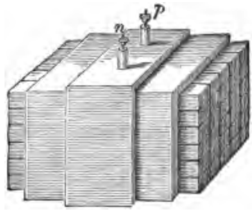


Fig. 126.

When a great number of pairs are formed into a battery, they may be conveniently arranged as in fig. 126, which shews one of 30 pairs. The odd faces, 1, 3, 5, &c., are exposed on the one side, and the even faces, 2, 4, 6, &c., on the other. The terminal bars are connected with the binding screws *n*, *p*. The interstices of the bars are filled with insulating matter (gypsum) to keep them separate, and the frame in which the whole is placed is of non-conducting matter. Such a pile in conjunction with a thermo-galvanometer forms a most delicate thermometer for radiant heat. When placed in a room, the temperature of which is equable all round, no current is produced; but if heat be radiated more on one side than another, a current ensues. If the hand, for instance, be brought near on the one side, a current indicates its radiant power; or if a piece of ice be brought near, a current is also shewn, but moving in the opposite way.

240. *Thermo-electric Inversion.*—It was discovered by Cumming that the thermo-electric order of the metals was not the same when the temperature of the junctions was high as when it was low, and that, in certain cases, the order was reversed. For instance, let a closed circuit be formed by soldering together the ends of a piece of iron and copper wire, and let the junctions be denoted by A and B. Also let a galvanometer be included in the circuit. If the junction B be kept at the ordinary temperature, and A raised, a current will be observed passing through A from the copper to the iron. This current will increase as the temperature of A is

raised, till it attains a maximum at a certain temperature T, and then begins to decrease. By still continuing to raise the temperature of A, the current will become zero, and finally set in the opposite direction. This phenomenon is called *thermo-electric inversion*, and the temperature T is called the neutral temperature. For a circuit of iron and copper the value of T is 284° C.

It is found that the current becomes zero when the temperature of the one junction is as much above T as the other is below it—that is, when the mean of the temperatures of the two junctions is T. Hence, in order to shew the reversal of the current, the easiest way is to heat both junctions, but the one a little more than the other. This may be readily accomplished by putting both junctions in the same flame, but the one in a slightly hotter part than the other.

It is evident that if both junctions, A and B, be below 284° C., the current will pass from copper to iron across the hot junction; whereas, if both are above 284° C., the current will pass from iron to copper across the hot junction. Hence, if one of the junctions, A, be at 284° C., and B be either hotter or colder than 284° C., the current will pass from copper to iron across the junction A.

Professor Tait has examined the whole subject of thermo-electric currents with great care, and has given the following expression for the thermo-electromotive force:

$$E = a(t_1 - t_2)\left\{T - \tfrac{1}{2}(t_1 + t_2)\right\}$$

where a is a constant depending upon the nature of the metals, t_1 and t_2 the absolute temperatures of the hot and cold junctions respectively, and T the absolute neutral temperature.

241. *Reversible Heating Effects—Peltier Effect and Thomson Effect.*—If two different metals be soldered together, and a current from a voltaic cell be sent through the junction, the junction will be heated when the current is in one direction, and cooled when the current is in the opposite direction. This reversible effect was first discovered by Peltier, and is usually called the Peltier effect. It is best seen by sending a current

through a bismuth and antimony junction as represented in fig. 127. When the current goes from bismuth to antimony, it cools the junction; when from antimony to bismuth, it heats the junction. If, for instance, water be placed in a hollow at either junction, cooled to 0° C., it will be frozen when the current passes from bismuth to antimony. When the junction of these two metals is put into the bulb of an air thermometer, so that a current can be sent through it either way, the air expands when the current goes from antimony to bismuth, and contracts when it goes in the opposite way.

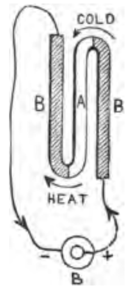


Fig. 127.

The Peltier effect can very readily be shewn by means of the thermo-pile as follows: Pass the current from a moderately strong voltaic cell through the thermo-pile for a minute or so, then disconnect the cell and join the thermo-pile in circuit with a galvanometer. A strong deflection will be observed, due to a thermo-electric current in the circuit; and this current arises from the opposite faces of the pile having been made to assume different temperatures by the passing of the voltaic current.

We know that a current in any electrical circuit produces a certain quantity of heat in overcoming the resistance, and that this amount of heat is, by Joule's law (sect. 226), proportional jointly to the square of the current strength, the resistance, and the time. Hence the quantity of heat produced in this way is entirely independent of the direction of the current in the circuit. It is different with the heating and cooling produced by the Peltier effect. Since this changes sign when the current is reversed, it obviously cannot be proportional to the square or any even power of the current strength, but must be proportional to the first or some odd power of the current strength. It has been found to be simply proportional to the current strength; and hence, if Π denote the coefficient of the Peltier effect for any junction —that is to say, the amount of heat absorbed or evolved at the junction by the passing of a unit current in a unit of

time—we have, for the whole heating effect, expressed in mechanical units, produced in a circuit of two metals, the following expression:

$$JH = C^2Rt \pm \Pi Ct.$$

242. The above equation gives us the means of calculating the value of Π, provided we can measure the total amount of heat produced in any circuit by the passage of a known current for a unit of time—first, when the current is in one direction, and secondly, when it is in the opposite direction. Let H_1 and H_2 be the total amounts of heat so produced, then, taking first the upper sign and then the lower, and dividing the whole by J, we have

$$H_1 = \frac{RC^2t}{J} + \frac{\Pi Ct}{J},$$

and

$$H_2 = \frac{RC^2t}{J} - \frac{\Pi Ct}{J}.$$

By subtracting these equations, we get

$$H_1 - H_2 = 2\Pi Ct;$$

from which we have $\Pi = \frac{J(H_1 - H_2)\frac{1}{2}}{2Ct}$;

or when the current is of unit strength and the time unity,

$$\Pi = \tfrac{1}{2}(H_1 - H_2).$$

Another reversible heating effect was predicted, from theory, by Sir William Thomson, and afterwards verified by him experimentally. It is hence called the Thomson effect. Suppose we have a closed circuit formed of iron and copper wire, and that one of the junctions, A, is at the neutral temperature, and the other, B, at a lower temperature. It is evident that a current will pass from copper to iron through A, and from iron to copper through B. By the Peltier effect there will be an evolution of heat at B. Since the current in the circuit is producing heat, and could be made to do mechanical work, there must be a disappearance of heat equivalent to the mechanical work so done, at some part of the circuit. This disappearance does not take place either at A or B; and hence, it must be looked for in the copper

and iron parts of the circuit themselves. It was found by Thomson that the current carries heat with it in a copper wire when it passes from a hot part to a cold part, and that it carries cold with it in an iron wire when it passes from hot to cold. The nature of the experiment which proves this will be understood from the following description. Insert, in a voltaic circuit, a piece of fine copper wire, and let the two junctions be kept at the freezing point. When the current passes, the wire will be heated, and if there were no reversible heating effect, the point of maximum temperature would be at the middle of the wire, and the temperature would gradually fall down as we approached either junction. As it is, however, the point of maximum temperature is observed to be a little past the middle point in the direction in which the current is going, and to change to the other side when the current is reversed. The opposite is found to be the case with a fine iron wire in the circuit.

243. *Thermo-electric Diagram.*—A thermo-electric diagram gives us the means of representing graphically, in a very clear and simple way, the electro-motive force and the Peltier and Thomson effects in any thermo-electric circuit. Such a diagram was first suggested by Sir William Thomson; and it has been brought to perfection by Professor Tait. It is constructed as follows:

Let Ox and Oy be two co-ordinate axes at right angles to each other; and let distances measured along Ox, that is, the abscissæ, represent temperatures reckoned from the absolute zero, that is, $-273°$ C. In order to draw what are called the thermo-electric lines for the several metals, we must first assume some metal as a standard; and then form thermo-electric circuits with it and each of the other metals in succession. The metal so assumed is usually lead, and for this reason, that the Thomson effect in lead, according to the experiments of Le Roux, is almost *nil*. Suppose now we wish to draw the thermo-electric line for copper. Having made a circuit of copper and lead, we find, by a series of experiments, the value of the electromotive force in the circuit, when the hot junction is half a degree above, and the cold junction half a degree below each particular temperature from 0° C. up-

wards. This is called finding the thermo-electric power of the metal with reference to lead. The values so found are represented in the diagram by vertical ordinates raised at the ends of the abscissæ which represent the temperatures; and when the ends of these ordinates are joined, the curve formed is the thermo-electric line. Professor Tait has shewn that this curve is a straight line for all metals between the limits of temperature 0° C. and 300° C.; and, hence, in order to simplify the diagram, we can assume Ox as representing the thermo-electric line for lead. The other lines will thus be straight lines inclined to Ox at various angles.

Let AB represent the copper, and CD the iron line, which cut each other at N; the abscissa, OH, of the point N will represent the neutral temperature for copper and iron. Let the hot junction be at the temperature $\beta°$, and the cold junction at the temperature $\alpha°$, represented by OF and OE respectively; then since the line BF is the thermo-electric power of copper, and CF that for iron, each with reference to lead; it follows that the difference, that is, CB, will represent the thermo-electric power of copper and iron for the mean temperature $\beta°$. Similarly, DA will represent the thermo-electric power of copper and iron for the temperature $\alpha°$.

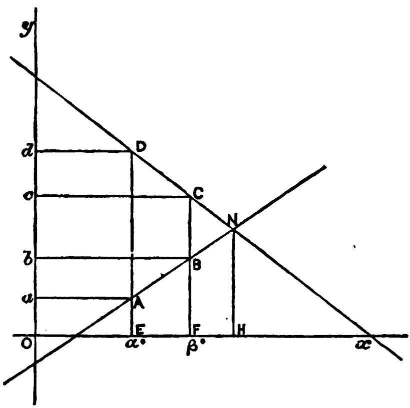


Fig. 123.

From the points A, B, C, D draw lines parallel to Ox, meeting Oy in a, b, c, d respectively; then the area ABCD will represent the electro-motive force of a copper and iron circuit, when the hot junction is at $\beta°$, and the cold junction

is at a°; and under the same circumstances, the area BC*cb* will be the Peltier effect at the hot junction, the area AD*da* the Peltier effect at the cold junction, the area BA*ab* the Thomson effect in copper, and the area CD*dc* the Thomson effect in iron.

CHAPTER XIX.

ELECTRO-MAGNETISM AND MAGNETO-ELECTRIC INDUCTION.

244. Allusion has already been made (sect. 184) to the discovery by Oersted of the action of a wire carrying an electric current on a magnetised needle placed in its neighbourhood. This discovery laid the foundation of the department of electrical science called *electro-magnetism*. It shews that the space surrounding every closed circuit in which a current is flowing constitutes a magnetic field, through which lines of force are passing, and at any point of which a magnetic pole will be acted upon by a certain resultant *electro-magnetic* force. It is our object to find, in any case, the direction and intensity of this force in relation to the form of the circuit, the strength of the current in it, and the distance of the magnetic pole from the circuit. This can be done most simply by substituting for the closed circuit what is called its *equivalent magnet*, or its *equivalent magnetic shell*.

245. *Equivalent Magnet and Equivalent Magnetic Shell.*—Suppose we have a small plane closed circuit AB (fig. 129), through which a current is flowing in the direction indicated by the arrow; and let the distance of this circuit from the magnetic pole m be very great in comparison with the dimensions of the circuit: then, it follows, from the researches of Ampère and Weber, that the action of AB on m is exactly the same as that of a small

Fig. 129.

magnet, SN, inserted perpendicularly through the circuit, subject to two special conditions. These conditions are, first, that the moment of the small magnet be equal to the area of the circuit a multiplied by the strength of the current C on it, that is, to aC; secondly, that the direction of the magnet from south pole to north pole be that of the insertion of a corkscrew through the circuit by rotating the wrist in the direction of the current. Such a magnet is called the equivalent magnet of the circuit.

Instead of the small magnet SN, we may imagine the whole circuit packed full of smaller magnets, provided the sum of the moments of all the magnets be equal to aC. If this were done, we should have all the north poles lying on one surface, and all the south poles on another, producing two parallel layers—the one of north magnetism, and the other of south magnetism, having the closed circuit for their common bounding edge. These two layers constitute a magnetic shell of strength C, which is the *equivalent magnetic shell* of the circuit.

Now, suppose we have a closed circuit ABCD, of any size and form; and let the space inclosed by it be filled in by a thin membrane of any form upon which we can draw a multitude of intersecting lines, cutting it up into four-sided spaces. Obviously, if the lines be close enough together, each of these spaces may be regarded as a plane surface. Let now a current of strength C, circulate round each of the small spaces *abcd*, as indicated by the inside arrows. It is evident from inspection that there are two equal and opposite currents in each line which separates one space from another. The effect of these is absolutely zero; and hence, the whole assemblage of such currents is identically equivalent to a

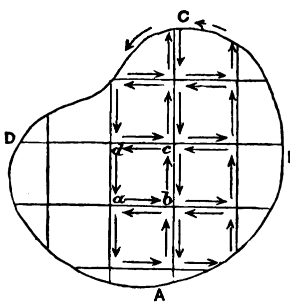


Fig. 130.

single current of strength C, circulating in the same direction round the single circuit ABCD. Conversely, for the current in any circuit ABCD, we can substitute a series of equal currents round the small circuits *abcd;* and from what has been already proved, we can substitute for each such small circuit its equivalent magnetic shell. When this is done, the whole assemblage of magnetic shells combine to form one single magnetic shell, having the circuit ABCD for its bounding edge; which is consequently the equivalent magnetic shell of the circuit ABCD. To assist the imagination, we may regard this equivalent magnetic shell as a very thin sheet of steel filling up the circuit, having one of its surfaces all north magnetism, and the other all south magnetism. The strength of such a shell at any point is measured by the product of the intensity of the magnetisation at that point into the thickness of the shell at the same point.

246. Having obtained the equivalent magnetic shell of any closed circuit, we have next to shew how, by means of it, we can get the potential at any point due to a closed circuit carrying a current. Before doing so, however, it will be necessary to explain what is meant by the *solid angle* subtended at a point by a closed circuit, or its equivalent magnetic shell. Let ABCD (fig. 131) be the closed circuit,

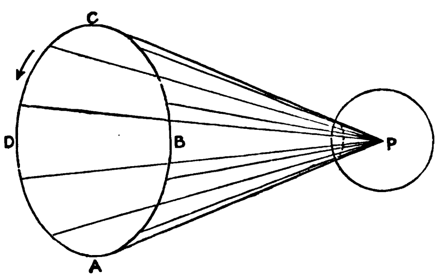


Fig. 131.

and P the point. From the point P, draw straight lines to every point of the circuit. These will lie on a conical

surface having its vertex at the point P. With P as a centre, describe a sphere of unit radius which will cut the conical surface. The curved line on the surface of the sphere formed by the intersection of the conical and spherical surfaces will evidently inclose a certain area on the unit sphere. It is this area which represents the solid angle subtended at P by the curve ABCD.

Now, let a current of strength C, circulate in ABCD ; C will also be the strength of the equivalent magnetic shell, having ABCD for its bounding edge. Now, if ω be the value of the solid angle subtended at P by ABCD, then the value of the potential at P, due to the closed circuit, is $C\omega$. We must here attend to certain conventions regarding signs. The solid angle is reckoned + when the area on the unit sphere is to the left of P and to the right of ABCD, and − when it is to the right of P and the left of ABCD. It is evident that if P move up to ABCD, the value of ω will gradually increase; and when P comes up to the positive side of the shell inclosed by ABCD, ω will be equal to the area of half the surface of the unit sphere, that is, it will be equal to 2π. It is equally evident that when P coincides with the negative surface of the inclosed shell, the value of ω will be -2π. Hence, at these two points, the values of the potential are respectively $+2\pi C$ and $-2\pi C$. Hence we see that if P be carried round the closed circuit from the negative to the positive side, the value of the potential changes from $-2\pi C$ to $+2\pi C$, that is, it changes by the value $4\pi C$. Since, in passing from the positive to the negative side of the shell, the potential changes from a positive to a negative value, it is manifest that at some point of the journey the potential must be zero. This will happen, for instance, for a plane closed circuit when the point P is in the plane of the closed circuit, as then the solid angle reduces to being a simple curved line on the unit sphere, which, of course, has no area.

If a series of surfaces be drawn passing through all those points at which the potential has the same value, these surfaces will be equipotential surfaces, and will all meet in the closed circuit. If lines be drawn everywhere at right

angles to these surfaces, these will be the lines of force due to the circuit, and will be the lines along which a free magnetic pole will tend to move under the influence of the electro-magnetic force due to the circuit.

We are now in a position to employ the results obtained to find the mutual action of currents on magnets, and of currents on other currents.

247. *Long straight Wire carrying a Current.*—Since every electrical current must form a closed circuit, in order to obtain this case we must conceive the closed circuit to be so large that the part of it which we are considering is entirely beyond the influence of the other parts of the circuit. Perhaps the easiest way of doing this is to imagine the straight wire to form one side of a huge rectangle of wire through which the current is circulating, and that the rectangle is so large that its opposite sides may be considered as infinitely distant from each other.

Let A and B represent the cross sections of two parallel sides of this rectangle made by the plane of the paper passing perpendicularly through them; and let P be the point on the plane of the paper at which the potential due to the current in A is required. The current is supposed to

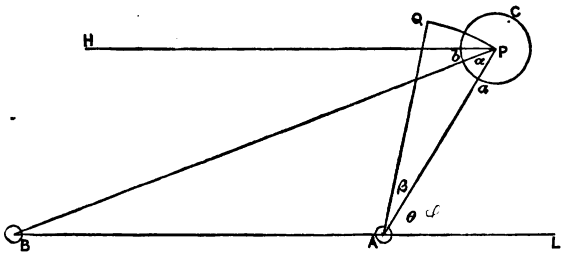


Fig. 132.

come vertically upwards through the paper at A, and to descend at B.

Describe round P a sphere of unit radius, and let the small circle *abc* be a section of it made by the plane APB.

It is evident, on a little reflection, that the solid angle subtended at P by the closed circuit is the area on the unit sphere contained between two planes, perpendicular to the plane of the paper, passing through the lines AP and BP respectively. It thus forms a *lune* on the unit sphere, and the area of this *lune* is clearly the same part of the whole surface of the sphere that the angle APB is of four right angles. Now it is known that the area of the surface of a sphere is four times that of its section through the centre, and hence the area of the unit sphere is four times that of the circle *abc*, that is, is equal to 4π. If we use circular measure, and denote the angle APB by a, we have for the value of the solid angle subtended at P:

$$\frac{a}{2\pi} \times 4\pi = 2a.$$

Now if B be supposed to move parallel to itself away from A, the angle APB will increase, and ultimately become equal to APH, that is, to PAL, which we denote by θ. Hence the true value of the solid angle is 2θ, and if C be the current in A, the value of the potential at P due to it is $2\theta C$.

248. From this we see at once that the potential is the same at every point of the line AP, and hence the equipotential surfaces will be a series of planes passing through A at right angles to the plane of the paper. Since the lines of force are always perpendicular to the equipotential surfaces, they will be a series of concentric circles in planes perpendicular to the wire, and having the wire passing through their common centre.

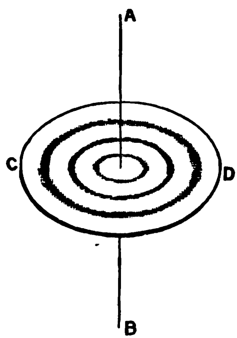


Fig. 133.

That such is the case can be readily shewn by an experiment. Pass a straight wire, AB (fig. 133), perpendicularly downwards through the centre of a circle of card-board, CD,

on which some fine iron filings are scattered. Send a pretty strong current through the wire, and gently tap the card-board, when the filings will be observed to arrange themselves in circles round the wire, tracing out the lines of force.

Having obtained the potential at P, we have next to obtain the strength of the field, or the magnetic force at that point. This is done by finding the rate of change of the potential along the line of force, PQ, which is part of a circle, with A as its centre. Denoting the magnetic force by H, and the potentials at P and Q respectively, by V_1 and V_2, and the angles QAL and PAQ by ϕ and β, we have:

$$H = \frac{V_2 - V_1}{PQ} = \frac{2C\phi - 2C\theta}{PQ} = \frac{2C(\phi - \theta)}{PQ} = \frac{2C\beta}{PQ}.$$

Now $$\beta = \frac{PQ}{PA}$$

Hence $$H = \frac{2C}{PQ} \cdot \frac{PQ}{PA} = \frac{2C}{PA};$$

that is, the magnetic force varies inversely as the distance of the point from the wire, and acts in a direction at right angles to the wire.

249. *Electrical Circuit placed in a Magnetic Field.*—We come next to consider the effect produced upon an electric circuit carrying a current, when the circuit is placed in a magnetic field, due either to the presence of a magnet or another electric circuit. For this purpose we substitute for the electric circuit its equivalent magnetic shell, and then we have merely to consider the effect of one magnetic system upon another. It can be shewn mathematically, as has been done by Clerk-Maxwell, that a rigid circuit so placed, and perfectly free to move, will set itself under the influence of the electro-magnetic forces acting upon it, so as to include the greatest possible number of lines of force; and that the direction of the current in the circuit will be related to the direction of the lines of force according to the cork-screw rule already mentioned. If, instead of being rigid, the circuit be flexible, it will also so set itself, and at the same time so alter its form, as to include the maximum number of

lines of force consistent with the geometrical conditions to which it is subject.

It results from these considerations, that, if an electric circuit experience any displacement in a magnetic field, the displacement will be such as to inclose more lines of force in the circuit; and that the amount of work done by the electro-magnetic force during the displacement will be proportional to the additional number of lines of force so inclosed. From this we can find the electro-magnetic force acting upon the circuit.

Let BE (fig. 134) be a part of a circuit carrying a current in the direction of the arrow; and for simplicity let us suppose the plane of the circuit to be perpendicular to the lines of force which are represented by the short parallel arrows.

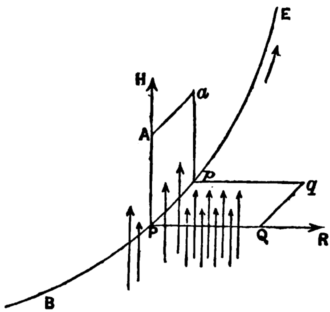


Fig. 134.

Take P*p*, an element, that is, a small part of the circuit, supposed straight, and of length equal to *a*. From P draw PH parallel to the lines of force, and cut off from it a part, PA, equal to the magnetic force, H, at the point P. It is evident that if the circuit P*p* be moved parallel to itself along PA, no alteration will be made in the number of lines of force passing through it. Hence no work will be done during such motion. The same is the case if the circuit be simply moved round in its own plane. Hence the direction of the electro-magnetic force acting upon P*p* must be perpendicular at once to PA and P*p*, that is, to the plane P*pa*A, A*a* and *pa* being drawn parallel respectively to P*p* and PA. Let PR be the direction of the resultant electro-magnetic force, and PQ be the displacement parallel to itself produced on the element P*p*. Complete the parallelogram PQ*qp*. Hence if C be the current strength in the circuit, the additional number of lines of force included in

the circuit by the displacement of Pp is represented by H multiplied by the area of the parallelogram PQqp, that is, by the product H $\times$ Pp $\times$ PQ. Also, since R is the resultant force, and PQ the space through which it acts, the amount of work done during the displacement is represented by the product R $\times$ PQ. Hence we have R $\times$ PQ $=$ H $\times$ C $\times$ Pp $\times$ PQ, and therefore R $=$ HC $\times$ Pp $=$ HCa.

Since the direction of the displacement is always such as to include more lines of force, it can, in any case, be determined by the following rule. Place a right-handed cork-screw in the direction of the resultant force PR. Turn the wrist in the direction from Pp to PH, that is, from the direction of the element to the direction of the magnetic force; then the circuit will be displaced in the direction of the longitudinal motion of the screw.

250. *Two parallel Currents.*—We shall now apply the above to find the resultant electro-magnetic force between two parallel currents, one of which is supposed to be infinitely long.

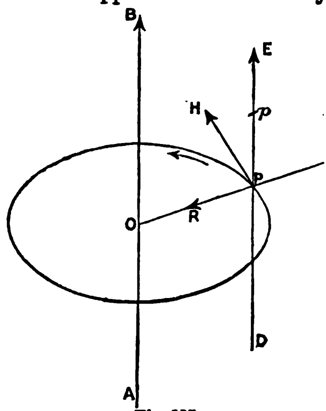


Fig. 135.

Let AB be an infinitely long straight wire carrying a current C, and DE a parallel wire carrying a current, C_1, in the same direction, as indicated by the arrows. Let the perpendicular distance between the two wires be r, and take Pp = a, an element of the circuit DE.

We have already shewn that the lines of force due to AB are concentric circles in planes perpendicular to AB, and having AB passing through their common centre. Hence PH is the direction of the magnetic force H at P. Hence the resultant electro-magnetic force R will be perpendicular to Pp and PH, that is, will be directed

towards AB. Also, if we think of the cork-screw being turned from Pp to PH, we see that Pp will move towards AB, that is, there will be an attraction between the wires. For the amount of the attraction we have $R = HC_1a$. For this case H has been shewn (sect. 248) to be equal $\frac{2C}{r}$. Hence we have

$$R = \frac{2CC_1a}{r}.$$

If the direction of the current in DE be reversed, there will be a repulsion instead of an attraction between AB and DE.

Hence we have the following general law which regulates the action between two parallel currents, namely: *That parallel currents in the same direction attract each other, and parallel currents in the opposite direction repel each other.*

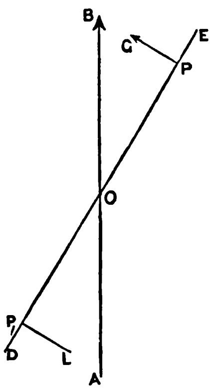


Fig. 136.

251. We come next to the case of two straight wires, carrying currents, inclined to each other at an angle, one of the wires being, as before, supposed infinitely long. Let AB be the infinitely long wire carrying a current from A to B, and DE another wire, carrying a current from D to E, inclined to AB, but in the same plane with it. DE is supposed to be insulated from AB at the crossing-point O.

At P the lines of force due to AB are perpendicular to the plane of the paper, seeing that they are circles in planes perpendicular to the paper. They are also directed through the paper from the reader. Similarly at P_1, the lines of force are perpendicular to the plane of the paper and towards the reader.

Hence at P the direction of the electro-magnetic force is in the line PG, perpendicular to PE. Similarly the force

at P_1 is in the direction P_1L. These two forces constitute a couple which tends to turn DE about O till it becomes parallel to AB.

If the current DE be reversed, the motion about O will be reversed.

Hence follows a second general law, namely—*That currents inclined to each other at an angle, attract when they both run to or from the crossing point, but repel when they run the one to and the other from the crossing point.*

252. Next let AB be as before an infinitely long straight current, and DE a current at right angles to it, but on one side. At P the lines of force due to AB are perpendicular to the plane of the paper, and directed through it. Hence we see at once, by applying the second law, or still better the cork-screw rule, that the direction of the resultant electro-magnetic is that of PL. Hence if DE be free to move parallel to itself, it will move in the direction from A to B, that is, in the same direction as the current in AB. By reversing the current either in AB or DE, DE will move in the opposite direction. From this we have a third general law, which may be thus stated: *When one current is perpendicular to another, the former current moves forwards parallel to the latter when it runs from it, and backwards when it runs to it.*

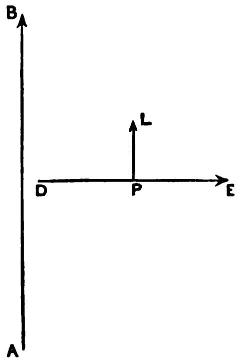


Fig. 137.

253. The above results can be illustrated experimentally in a variety of ways. The first two may be experimentally illustrated by an apparatus such as that shewn in fig. 138. The rectangle *cdef* is movable round the pins *a* and *b*, resting on two mercury cups, which act as binding screws to complete contact. The arrangement is such that while the rectangle *cdef* is moving about its axis, a current can continue steadily to flow in it. Further description is unnecessary, as the diagram explains itself. It can be easily

understood, that a wire conveying a current may be placed, with regard to the different parts of the rectangle, so as to illustrate the first two laws. Thus, if a wire conveying a downward current be brought near to *cd*, so as to be parallel to it, attraction will take place; if it be presented to *fe*, repulsion will ensue. A current-wire held horizontally with respect to *cd*, can be placed so as to make the currents both tend to the crossing-point between them, or the opposite, so as to illustrate the second law. It may be objected, that in this apparatus we cannot examine the effect on one part of the current without also taking in the other parts of the rectangle; but these last may be made to stand comparatively so far off as not to affect the main result.

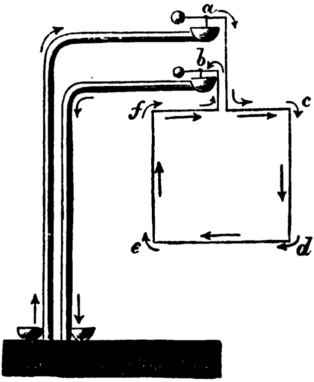


Fig. 138.

254. The third law may be shewn by an apparatus such as that in fig. 139. A is a small circular trench containing mercury, surrounded by a coil of insulated copper wire, *ww'*. The metal rod, BB, is surmounted by a small cup of mercury. A light copper wire, *bacd*, is poised on a fine point in the cup *n*, and its lower ends, *d*, *b*, dip into the mercury of the trench. The circuit is so arranged that the current enters at *w*, traverses the coil, passes to BB (connection not shewn), which it ascends; at the cup, entering the copper wire, it splits into two branches, descends along *ab* and *cd* to the mercury, and leaves finally for the battery at *o*. As soon as the circuit is closed, the wire, *bacd*, enters into constant rotation. In the coil, the current moves contrary to the hands of a watch; the wire, according to the third law, moves backward upon it in the direction of the hands of a watch. In the figure, the

horizontal parts of the current, *na* and *nc*, are so far above the current as to affect the motion slightly, if at all. But if the upright branches *ab* and *cd* were short, so as to leave the motion almost entirely to *na* and *nc*, the wire would still rotate as before; for the currents *na* and *nc* are also perpendicular to the current of the coil, though in a different but parallel plane, and both run towards it, thus standing in the same relation as before. If the current be reversed, the motion of the wire is also reversed.

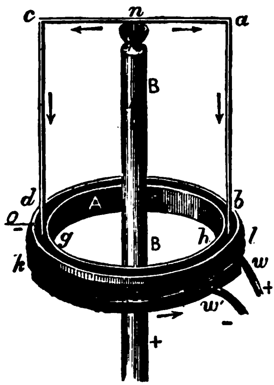


Fig. 139.

255. A curious consequence is considered to follow from the second law—namely, that since two parts of a straight line may be regarded as standing at a very obtuse angle to each other with reference to a point in it, any point in the straight line may be looked upon as the crossing-point of its two parts. As at the point taken we find the one part of the current approaching, the other leaving it, the two parts of the current repel each other. Hence *the various parts of a current, in a straight line, repel each other.* Faraday, in illustration of this, bent a wire in the form of a horseshoe, and made each end of it dip into a separate vessel containing mercury. The wire was partly supported by the mercury, and partly by the beam of a delicate balance. When the poles of a battery are put into the vessels, the wire loses weight, from the repulsion of the mercury conveying the same current as itself. This experiment, it must be confessed, is not quite decisive, as the repulsion may arise from the peculiar action of a fluid on a solid part of the circuit. The mutual action of currents on each other was first elucidated by Ampere in 1825.

256. *Currents on Magnets.*—If we put a north magnetic pole in the neighbourhood of a straight wire carrying a current, it will, as we have seen, move round the wire in a circle

tracing out a line of force. A south magnetic pole similarly placed will also move round the wire, but in the opposite direction. Suppose now that we place near the wire a long, perfectly flexible magnet, such as we may imagine made from a long thin strip of very flexible watch mainspring; since the north pole goes round the wire in one direction, and the south pole in the other direction, the effect will be that the flexible magnet will become coiled round the wire in the form of a close spiral. Conversely, if we imagine the magnet fixed, and the wire carrying the current flexible and free to move, then the wire will coil itself round the magnet. This last result can be easily illustrated by experiment as follows:

Let NS be a long strongly magnetised steel bar placed vertically, and let ABC be a long narrow strip of some very flexible metallic foil suspended near the magnet, and through which a current can be passed. When a moderately strong current is sent through ABC, the loose portion of the strip will be seen to coil itself round the pole of the magnet; and by reversing the current it will uncoil itself, and again coil round the magnet in the opposite direction.

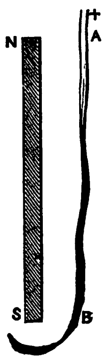


Fig. 140.

257. *Law of the action of Currents on Magnets.*—The law of the action of currents on magnets has been investigated experimentally by Biot and Savart in the following way. They suspended, by means of a cocoon fibre, a short magnetic needle in the neighbourhood of a straight wire carrying a current of constant strength. By means of a fixed magnet, the action of the earth's magnetism on the movable needle was as far as possible neutralised; and the whole apparatus was inclosed in a glass case to prevent disturbance from currents of air. They first found that, in all positions, the resultant force, due to the current, acting upon the magnetic + pole, was perpendicular to the plane passing through the wire and the pole. The magnet, in consequence, set itself so that its axis was at right angles to the line drawn from its middle point

perpendicular to the wire carrying the current. They next varied the distance of the magnet from the wire, and observed, at the various distances, the period of oscillation of the magnet, when disturbed, under the influence of the current. From this they found that the intensity of the electromagnetic force acting upon the pole of the magnet varied inversely as the perpendicular distance of the pole from the straight wire. Now, in order to obtain this result for the action of the whole wire, we must suppose that each element of the wire acts upon the pole with a force which varies directly as the length of the element, and inversely as the *square* of its distance from the pole; or, to put it otherwise, by making this latter assumption we can shew mathematically that the experimental result must follow. The following is the proof usually given.

Let AB and A′B′ be two parallel straight wires carrying equal currents at different perpendicular distances, ME and ME′, from the magnetic pole M. Let CD and C′D′ be elements of the currents cut off by the lines MCC′ and MDD′, which are supposed inclined to each other at a very small angle. Also let f and f' denote the forces exerted by the elements CD and C′D′ respectively upon the magnet-pole M. Then, according to the above assumption, we have

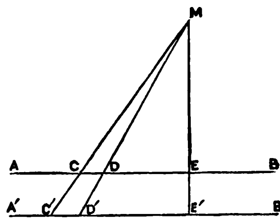


Fig. 141.

$$f : f' :: \frac{CD}{CM^2} : \frac{C'D'}{C'M^2};$$

that is,
$$\frac{f}{f'} = \frac{CD}{C'D'} \cdot \frac{C'M^2}{CM^2}.$$

But from similar triangles we have

$$\frac{CD}{C'D'} = \frac{CM}{C'M} = \frac{EM}{E'M}.$$

Therefore
$$\frac{f}{f'} = \frac{\text{EM}}{\text{E'M}} \cdot \frac{\text{E'M}^2}{\text{EM}^2} = \frac{\text{E'M}}{\text{EM}};$$

that is,
$$f : f' :: \frac{1}{\text{EM}} : \frac{1}{\text{E'M}}.$$

Hence the forces exerted by the elements CD and C′D′ vary inversely as the distances EM and E′M; and since CD and C′D′ are any elements, what is true of them is true of all the others, and hence the forces exerted by the whole wires AB and A′B′ vary inversely as the distances EM and E′M.

Now, so long as we are dealing with the elements of currents merely, it matters not whether we consider them to be elements of straight currents, or elements of currents of any other form; and hence, by summing up the above results, we have the following expression for the general law which regulates the action of currents, on magnets: *The force with which each element (small part) of a current acts on a magnetic pole, stands at right angles to the plane passing through the element and the pole, and is inversely proportional to the square of the distance of the element from the pole.*

258. *Circular Current.*—We can now make use of the above law to find the force exerted by a circular current on a magnetic pole placed at a point on its axis—that is, on the straight line drawn perpendicular to the plane of the circle through its centre.

Let ABC be the circular wire carrying a current, C, and let the radius OA = a. Also let AB be an element of the current of length s. Let M be a magnetic pole of strength unity placed on the axis OMF. The force f, exerted by the element AB on M, is perpendicular to the plane AMB. Denote it by the line ME of length f.

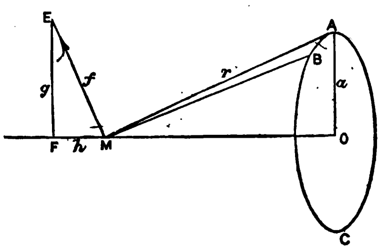


Fig. 142.

Then, according to the above law, we have $f = \frac{Cs}{r^2}$, when $r = AM$.

Now, the force f can be resolved into two components, one parallel to OF, and the other perpendicular to it. Let h and g be these components respectively. From the similar triangles, FEM and OAM, we have $\frac{MF}{ME} = \frac{OA}{AM}$, and therefore

$$\frac{h}{f} = \frac{a}{r}\text{; that is, } h = \frac{af}{r}.$$

By substituting for f its value $\frac{Cs}{r^2}$, we have

$$h = \frac{a}{r} \times \frac{Cs}{r^2} = \frac{Cas}{r^3}.$$

Now, it will be at once seen that a precisely similar expression will be got for each element of the circuit, and that the value of r for each element is the same, and hence the value of the total component of the force parallel to OF will be got by summing up all the fractions similar to $\frac{Cas}{r^3}$. Let H denote this total component, then,

$$H = \frac{Ca}{r^3} \times \text{the circumference of circle ABC},$$

that is,

$$H = \frac{2\pi a^2 C}{r^3}. \qquad (1)$$

Since each element of the circuit has an equal diametrically opposite element, it is evident that the components, corresponding to g, due to each pair of such elements, must be equal and opposite forces, and hence will destroy each other. Hence equation (1) gives the total force exerted by the circular circuit on a unit pole at M.

By supposing M to move up to O, so that r becomes equal to a, we obtain the following expression for the force exerted by a circular current upon a unit pole placed at its centre—namely:

$$H = \frac{2\pi a^2 C}{a^3} = \frac{2\pi C}{a}.$$

259. *Electro-magnetic Rotations.*—A great many pieces of

apparatus have been devised to illustrate the continuous rotation of magnets under the influence of currents, and *vice versâ.* The apparatus by which Faraday effected these rotations was as follows:

M and N (fig. 143) are two vessels containing mercury, with wires entering them below, so as to effect their communication with the poles of a battery; *b* is a small powerful magnet, tied by a thread to the wire at the bottom; F is a magnet, fixed to the bottom of the vessel N; *d* is a copper wire, hung by a metal hook. When the current passes, as in the figure, the movable magnet *b* rotates round the fixed wire *e*, and the movable wire *d* revolves round the fixed magnet F, in the direction according to the rules just given. If the upper ends of F and *b* be south poles, the rotation of *b* will be in the same direction as the hands of a watch, and of *d* in the opposite way.

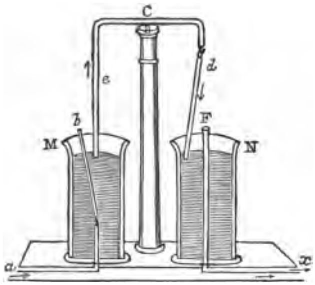


Fig. 143.

260. Another very instructive piece of apparatus was invented by Barlow, and is usually called Barlow's Wheel. It is represented in fig. 144. A is a copper disc movable on a stirrup, and having its lower edge dipping in the mercury cup C.

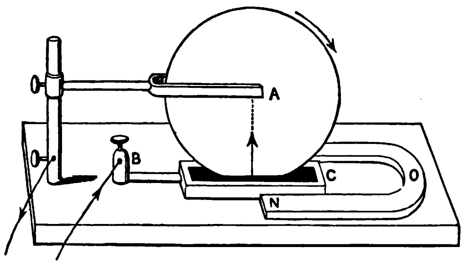


Fig. 144.

A powerful horseshoe magnet, NO, is placed so that the wheel is exactly between the poles. The current enters at B, thence to the mercury cup C, from which it ascends a radius of the wheel to the stirrup, and from this to the battery. The lines of force due to the magnet are, at the point where the wheel dips into the mercury, perpendicular to the plane of the wheel, and hence perpendicular to the radius along which the current ascends. By reflecting on the rule already given (sect. 249), we see that the wheel will be set in rotation in the direction of the arrow.

261. *Action of the Earth on Currents.*—The lines of magnetic force on the earth's surface are parallel to the dipping-needle, and currents have a tendency to move at right angles to them. In order to ascertain the action on any portion of a current by the lines of magnetic force, we have simply to project it on a plane at right angles to the lines of force or to the dipping-needle. If the line to be projected lies at right angles to the dipping-needle, then its projection on the plane will be of the same length as itself, and the action of the earth-magnetism will be to urge it perpendicular to the lines of force and to itself, and in a direction determined by the position of the poles of the earth to it. If the line be parallel to the lines of force, then its projection will be a point or the section of the wire; and it is manifest that the line in this position has no tendency to displacement under magnetic influence. The force of terrestrial magnetism on it is null. A line between these two positions will appear shortened when projected on the plane, and the direction in which it is urged will be indicated by the perpendicular to the projected line. The shorter the line becomes in projection, the less it is exposed to the displacing influence of terrestrial magnetism.

Let us apply the principles just stated to the case of the revolving wire, fig. 139, when the coil is placed out of the circuit. Let us suppose the lines of magnetic force resolved into two sets, horizontal and vertical lines. Let us confine our attention to one half, *nab*, of the wire. The vertical lines of force have no influence on the vertical part, *ba*, because it is parallel with them, and its projection on a

horizontal plane would be a point. To *na*, whatever position it occupies in its circle of rotation, the vertical lines will be at right angles, and exert their full force on it. *na* rotates in presence of the north pole of the earth, which, according to our way of speaking, is a south pole; it will therefore rotate contrary to the hands of a watch. Let us now see how the horizontal lines act. *ab* stands always perpendicular to them, whatever be its position. It will accordingly be urged to the right as far as it can go, which is in a position in which it lies east of BB. Here it will be in stable equilibrium, and it will resist being moved westwards one way or other. In this position *na* would be urged upwards by the horizontal lines, which, from its mode of suspension, cannot take place. The effect of the horizontal lines on *na* is to move it downwards in its west, and upwards in its east position, but not to interfere with its motion in a horizontal plane. In the position in which *nab* stands east of BB, it becomes a question of strength whether *na* shall carry it on, or *ab* keep it standing. If it is to rotate, *ab* must be made shorter than *na*. If both halves be now taken into account, *cd* and *ab* will have a tendency to place themselves both east of BB; they will therefore counteract each other, and leave the motion of the wire to *na* and *nc*, which will keep it in constant motion.

On a closed circuit, such as that of fig. 138, the effect of terrestrial magnetism will be to place the plane of it at right angles to the magnetic meridian. The horizontal parts will have no effect. The whole will be left to the vertical currents, which, passing, the one up, the other down, will place themselves, *cd* to the east, *ef* to the west. It is from the conflicting action of its parts that a closed circuit, as a whole, cannot continue to rotate in a magnetic field.

ELECTRO-MAGNETISM.

Electro-magnetism includes all phenomena where magnetism is produced by an electric current. As of great importance in understanding these phenomena, we must first give the properties of the solenoid.

262. *Solenoid.*—As originally defined by Ampère, a *solenoid* consists of an arrangement of circular currents, of infinitely

small radius, placed side by side, so that the planes of all the circles are perpendicular to the line passing through their centres. This line is called the axis of the solenoid, and may be either straight or curved. When straight, the circular currents lie on the surface of a cylinder as represented in fig. 145. The currents are also supposed to be all of equal strength, and to flow all in the same direction.

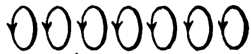


Fig. 145.

A solenoid of any size can be imagined as made up of a bundle of such elementary solenoids laid side by side parallel to each other. A section of such a solenoid made by a plane perpendicular to its axis is represented in fig. 146. It will be at once observed that the currents in the adjacent elementary solenoids must destroy each other, seeing that they are equal, and flow in opposite directions; and that there is left as effective only the current in the external circle ABC. Such a system of external currents is thus equivalent to the whole number of elementary solenoids.

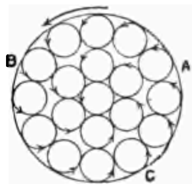


Fig. 146.

In order to find the strength of the magnetic field, or, what is the same thing, the intensity of the magnetic force at a point on its axis, due to the solenoid, we proceed as follows: Let PQ be the solenoid, of length l and radius r; and let C be the strength of each circular current. Let M be a unit magnetic pole placed on the axis BAM. We may imagine (sect. 245) each circular current to be replaced by its plane equivalent magnetic shell consisting of two equal layers of magnetism—the one, north-magnetism, on the side facing A; and the other, south-magnetism, on the side facing B. Let σ be the surface-density of each of these

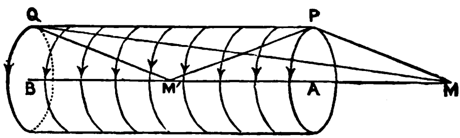


Fig. 147.

layers, and τ the thickness of the shell, then the strength of the shell is represented by $\sigma\tau$. But this is (sect. 245) also equal to the current strength C. Hence we have $\sigma\tau = C$, or $\sigma = \frac{C}{\tau}$. Now, for the whole quantity of magnetism on each face of the shell, we must multiply σ by the area of the circular face. Denoting this area by a, we have on each magnetic shell a quantity of north-magnetism equal to $+\frac{aC}{\tau}$, on the one side, and a quantity of south-magnetism, equal to $-\frac{aC}{\tau}$, on the other side. Now, since the equivalent magnetic shells arising from all the circular currents are close together, it is evident that the north-magnetism on the one side of one shell will exactly neutralise the equivalent amount of south-magnetism on the side next to it of the adjacent shell; and that in consequence there will be left, as effective on external points such as M, only the layer of north-magnetism, $+\frac{aC}{\tau}$, on the end, A, of the solenoid, and the layer of south-magnetism, $-\frac{aC}{\tau}$, on the other end, B. If n be the number of circular currents in the length l of the solenoid, evidently, $\tau = \frac{l}{n}$; and since r is the radius of the solenoid, $a = \pi r^2$. Hence, by substituting, we have for the above quantities of magnetism the values $+\frac{\pi r^2 nC}{l}$ and $-\frac{\pi r^2 nC}{l}$ respectively. It now only remains to calculate the force which these quantities of magnetism together exert on the unit pole placed at M. This will give the strength of the magnetic field at that point which we may denote by H. The calculation requires, however, higher mathematics than can be given here, and hence we give only the result, which is singularly elegant, namely:

$$H = \frac{2\pi nC}{l}\left(\frac{BM}{QM} - \frac{AM}{PM}\right);$$

or calling the angles QMB and PMA, χ' and χ respectively:

$$H = \frac{2\pi nC}{l}(\cos\chi' - \cos\chi). \tag{1}$$

The same expression could also be obtained by applying the formula of sect. 258 to each circular current, and adding the results.

If the unit pole be inside the solenoid, as at M′, it is obvious that the angle χ becomes obtuse, and its cosine consequently negative. Hence for this case,

$$H = \frac{2\pi nC}{l}(\cos\chi' + \cos\chi). \tag{2}$$

When the length of the solenoid is great in comparison to its diameter, the angles χ' and χ in (2) become very nearly both 0, and their cosines consequently each very nearly equal to 1. Hence for this case,

$$H = \frac{2\pi nC}{l}(1 + 1) = \frac{4\pi nC}{l}. \tag{3}$$

This shews that the strength of the field inside a long narrow solenoid is very approximately uniform.

The solenoids spoken of above are only typical, and cannot be realised in practice. As usually constructed, a solenoid (fig. 148) consists of an insulated copper wire bent in the form of a spiral, and having its ends bent backwards along the axis to the middle point, and then bent upwards at right angles between two coils of the spiral. It is manifest that in such an arrangement the currents do not exactly fulfil the solenoidal condition inasmuch as their planes are not exactly perpendicular to the axis. We can, however, imagine the current in each coil of the spiral as resolved into two components, of which the one is a circular current perpendicular

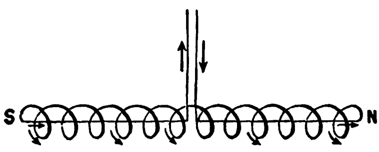


Fig. 148.

to the axis, and the other a short straight current parallel to the axis. The action of all the straight currents is exactly neutralised by the equal and opposite current along the axis, and hence the arrangement, on the whole, acts precisely as a typical spiral. Such a spiral carrying a current is found experimentally to exhibit all the properties of a straight bar-magnet. If suspended on an Ampère's stand (fig. 138) so as to be movable in a horizontal plane, it sets itself with one end north and the other south, exactly like an ordinary declination needle. If suspended so as to be free to move in the plane of the magnetic meridian, it sets itself parallel to the dipping-needle. The ends of the spiral are also acted upon by, and act upon, a magnet exactly as if it were itself a magnet. Two solenoids also act upon each other as if they were magnets, like solenoid poles repelling, and unlike attracting each other, exactly as is the case with the corresponding magnet poles.

263. *Ampère's Theory of Magnetism.*—This theory forms the link between magnetism and current electricity, and gives a simple explanation of the electric action and constitution of magnets. Ampère considers that every particle of a magnet has currents circulating about it in the same direction. A section of a magnet, according to this theory, is shewn in fig. 149. All the separate currents in the various particles may, however, be considered to be equivalent to one strong current circulating round the whole (fig. 150). We are to look upon a magnet, then, as a system, so to speak, of rings or rectangles, placed side by side, so as to form a cylinder or prism, in each of which a current in the same direction is circulating. Before magnetisation, the currents run in different directions, so that their effect as a system is lost, and the effect of induction is to bring them to run in the same direction. The perfection of magnetisation is to render the various currents parallel to each other. Soft iron, in consequence of its offering no resistance to such a disposition,

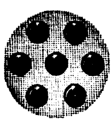


Fig. 149.

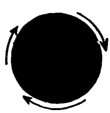


Fig. 150.

becomes more powerfully magnetic under induction than steel, where such resistance exists.

Ampère's theory explains very satisfactorily why like poles repel, and unlike attract. Figs. 151 and 152 shew this. Two north poles near each other (fig. 151) have opposite currents

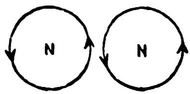


Fig. 151.

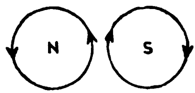


Fig. 152.

on their adjoining side, and repel each other in consequence. A north and a south have similar currents, and attract (fig. 152).

If the north pole of a magnet were placed parallel to BB in fig. 139, the coil being left out of the circuit, the rotation would take place as shewn in the figure; if the south pole be put in the same place, the motion of the wire will be reversed. According to Ampère's theory, it may be also easily explained why a closed circuit rests in equilibrium at right angles to the magnetic meridian, and why the axis of a magnet which lies in the axis of a series of such closed circuits places itself in the meridian. The earth, being a magnet, has currents circulating about it, which must be from east to west, the north pole of the earth being, in our way of speaking, a south pole. A magnet, then, will not come to rest till the currents moving below it place themselves parallel to and in the direction of the earth's currents. This is shewn in fig. 153, where a section of a magnet is represented in its position of rest with reference to the earth-current. The upper current being farther away from the earth-current, is less affected by it, and it is the lower current that determines the position. A magnetic needle, therefore, turns towards the north to allow

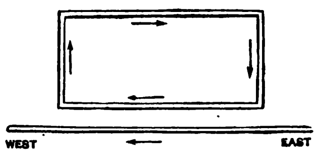


Fig. 153.

the currents moving below it to place themselves parallel to the earth's current.

264. *Electro-magnets.*—Perhaps the strongest proof of the truth of Ampère's theory is the fact that when a current wire is coiled round a piece of soft iron, the iron becomes for the time powerfully magnetic. This can be shewn by inserting an iron rod in the axis of a solenoid, when the magnetic effect of the latter is seen to be greatly increased, inasmuch as the iron itself becomes magnetic under the influence of the currents surrounding it. The cause of this increase can be readily understood from the results already given. Suppose

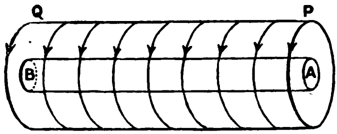


Fig. 154.

PQ to be a solenoid of length l, sectional area a; and let the number of circular currents on it be n. Also let AB be an iron rod of length l, and sectional area a', inserted in the axis. Further, let k be the coefficient of magnetic induction of the iron rod; by which is meant, that k is the quantity of magnetism separated, by unit magnetic force across unit area of any section of the iron rod perpendicular to the lines of force, that is, in this case perpendicular to the axis. Now, in order to find the whole quantity of magnetism separated across any section of the rod, we must multiply k by the area of the section, and by the magnetic force acting upon it. The intensity of the magnetic force acting at any point within the solenoid, is given by equation (3) (sect. 262), and is equal to $\frac{4\pi nC}{l}$, if C be the current strength in the solenoid. Hence the quantity of magnetism separated across any section of the rod is $\frac{4\pi nC}{l}a'k$. But this is also the quantity of magnetism across the end section A. Hence the strength of the iron pole A is $\frac{4\pi nC}{l}a'k$. From sect. 262 we find the strength of the solenoid pole to be $\frac{anC}{l}$. By adding

these two results, we find the total strength of the pole due to both the iron rod and the solenoid to be

$$\frac{anC}{l} + \frac{4\pi nC}{l}a'k = \frac{nC}{l}(a + 4\pi a'k).$$

This shews that a marked increase is produced in the strength of the solenoid by the mere insertion of an iron rod in its axis. The general form of an electro-magnet is shewn in fig. 155. It consists of a round bar of soft iron bent into the horseshoe form, with an insulated wire coiled round its extremities. When a current passes through the coil, the soft iron bar becomes instantly magnetic, and attracts the armature with a sharp click. When the current is stopped, this power disappears as suddenly as it came. Electro-magnets far outrival permanent magnets in strength. Small electro-magnets have been made by Joule which support 3500 times their own weight, a feat immeasurably superior to anything performed by steel magnets. When the current is of moderate strength, and the iron core more than a third of an inch in diameter, *the magnetism induced is in proportion to the strength of the current, and of the number of turns in the coil.* It is of no importance whether the coils be placed all over the magnet or accumulated at the ends. When the bar is thinner than one-third of an inch, a maximum is soon reached beyond which additional turns of the wire give no additional magnetism; and even when the core is thick, the advantage gained by increasing the number of coils may be lost by the long circuit reducing the strength of the current. The maximum that can be reached is, in different magnets, proportional to the area of section, or to the square of the diameter of the core. It is found also, when the mass of the armature is equal to that of the core, that *the weight which the*

Fig. 155.

magnet sustains is in proportion to the squares of the strengths of the currents. The length of the electro-magnet has no other advantage than that of insulating the poles, the one from the other. When the core consists of a bundle of insulated wires, it is capable of greater magnetisation than when it is solid. The rust that sooner or later forms on iron wires is sufficient insulation. The electro-magnet, from the ease with which it is made to assume or lay aside its magnetism, or to reverse its poles, is of the utmost value in electrical and mechanical contrivances. That the electro-magnet may quickly acquire and as quickly lose its magnetism on closing and breaking the circuit, it is necessary that the iron be perfectly pure or soft, and well annealed. It is also necessary that the armature be kept just short of touching, for when it is in contact, a residuum of the induced magnetism lingers in it and in the core after the current stops. Under current induction the various molecular currents, according to Ampère's theory, place themselves parallel to each other, and act powerfully in concert. The direction of the current and the nature of the coil being known, the poles are easily determined by the cork-screw rule.

265. *Magnetic Tick.*—When an iron rod is made to rest on a sounding-board, such as the body of a fiddle, and placed in the centre of a powerful coil, each time the current is broken a distinct tick is heard from the rod. If a file be placed in the circuit, so that a wire when it slides along will alternately close and open the circuit, the rasping noise of the wire sliding along the file will be distinctly rendered by the rod, each interruption giving rise to a tick; the series of ticks being in the same order exactly as the series of noises at the file. According to Wertheim, the tick is due to the sudden shortening which the rod experiences on being demagnetised. He shewed that at magnetisation the rod was lengthened but very slightly. According to Joule, if the rod be magnetised to saturation, the lengthening amounts to $\frac{1}{270000}$th of its length. The tick is heard more distinctly if, instead of the rod, a piece of thin sheet-iron be rolled up so that its edges just overlap. The application of this magnetic sound to the conveying of sounds, is described under Telephone.

CHAPTER XX.

GALVANOMETERS.

266. *Galvanometer.*—A galvanometer is an instrument for measuring the strength of a current by means of the magnetic action which the current exerts. It consists essentially of a coil or coils of wire surrounding a freely suspended magnetised needle; and the current strength is deduced from the deflection produced by it on the needle.

Galvanometers may be divided into two great classes—first, those which are used to measure strong currents; and, secondly, those which are used to detect and measure feeble currents.

Examples of the first class are the Tangent Galvanometer and the Sine Galvanometer; of the second class, sometimes also called *Sensitive* Galvanometers, are the *Astatic* Galvanometer, and Thomson's *Reflecting* Galvanometer.

267. *Tangent Galvanometer.*—This instrument is shewn in fig. 156. It consists of a thick strip of copper, or of several coils of insulated wire, bent into the form of a circle, from one to two feet in diameter, and with a small magnetic needle moving on a graduated circle at its centre. When the needle is small compared with the diameter of the coil, it may be assumed that the needle always moves in a magnetic field of uniform strength. This being the case, *the strength of the current circulating in the ring is proportional to the tangent of the angle of deflection of the needle.* The angle of deflection is reckoned from the plane of the ring, which is placed parallel to the magnetic meridian. Fig. 157 shews

Fig. 156.

how this may be proved. Let MM be the magnetic meridian, and let AB represent the wire coil looked down upon from above. Let NS be a magnetised needle, of length $2l$, suspended at the centre of the coil; and let the magnetic strength of each pole be m. Let the angle of deflection of the needle from the plane of the ring be δ. The force exerted by the coil on the pole N is perpendicular to the plane of the coil, and is (sect. 258) equal to $\frac{2\pi Cm}{a}$, where C is the current strength and a the radius of the coil. The moment of this force about O is $\frac{2\pi Cm}{a}\,\mathrm{OX} = \frac{2\pi Cm}{a}\,l\cos\delta$. Also if H be the horizontal component of the earth's magnetic force, the moment of the force exerted by the earth on the pole N is $\mathrm{H}m \times \mathrm{NX} = \mathrm{H}lm \sin\delta$. Now if the needle be in equilibrium, at the deflection δ, under the influence of these two forces, these two moments must be equal. Hence, we have

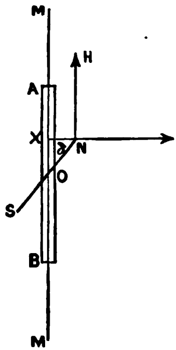


Fig. 157.

$$\frac{2\pi Cm}{a}\,l\cos\delta = \mathrm{H}lm\sin\delta;$$

$$\therefore \mathrm{C} = \frac{a}{2\pi}\,\mathrm{H}\tan\delta. \qquad (1)$$

If there be n coils of wire in the circular ring, and if a be the mean radius of the ring, this equation becomes:

$$\mathrm{C} = \frac{a}{2\pi n}\,\mathrm{H}\tan\delta. \qquad (2)$$

The above equations are not strictly accurate, seeing that the needle, NS, does not move in a magnetic field of perfectly uniform strength. The farther the needle is deflected from the plane of the coil, the weaker is the action of the current upon it; and the current strength is not strictly proportional to the tangent of the angle of deflection. In order to do away with this inaccuracy, as far as possible, Helmholtz has adopted the modification of the tangent galvanometer repre-

sented in skeleton in fig. 158 *a*, and in perspective in fig. 158 *b*. A and B (fig. *a*) are two circular coils of equal radius through which the same current flows in the same direction. These coils are placed with their planes vertical and parallel to each other, and the distance, OO′,

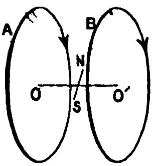


Fig. 158 *a*.

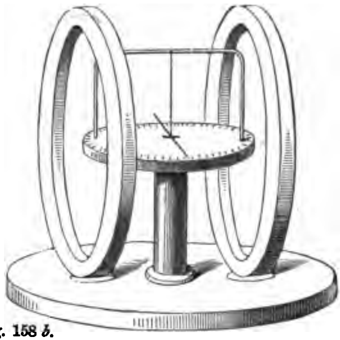


Fig. 158 *b*.

between the centres is made equal to the radius of either coil. The needle, NS, is suspended at the middle point of the common axis, OO′, of both coils. With this arrangement, it can be shewn mathematically that the magnetic field surrounding NS, provided its length be very short in comparison to the radius of the coils, is very nearly uniform, and hence that the current strength is very nearly proportional to the tangent of the angle of deflection.

In Gangain's arrangement only one coil, A, is used, all other things remaining the same.

268. *Sine Galvanometer.*—The construction of the *sine* galvanometer is very similar to that of the tangent galvanometer represented in fig. 158—the essential difference between them being, that, in the sine galvanometer, the wire-coil can be rotated about a vertical axis, and so made to follow the needle during its deflection. The angle of rotation is observed by means of a horizontal scale and vernier. In use the instrument is first placed with the plane of the coil parallel to the magnetic meridian, the axis of the needle being then in the plane of the coil. When the current is sent through the coil, the needle is deflected, and then the coil is slowly rotated till its plane again coincides with the axis of the needle. The angle of rotation, δ, is then observed. Let MM (fig. 159)

be the magnetic meridian with which the plane of the coil originally coincides; and let AB and NS be the altered positions of the coil and needle, after rotation through the angle δ. Since the force exerted by the current upon the pole N is always perpendicular to the plane of the coil, the moment of this force about O will, in this case, be $\frac{2\pi Clm}{a}$, the letters having the same signification as before. Also the moment of H, the horizontal component of the earth's magnetic force, about O, is, as before, $Hlm \sin \delta$. These moments being equal in the position of equilibrium, we have

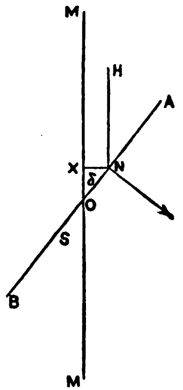


Fig. 159.

$$\frac{2\pi Clm}{a} = Hlm \sin \delta.$$

Hence $$C = \frac{a}{2\pi} H \sin \delta.$$

C is therefore proportional to the sine of the angle of deflection. The sine galvanometer is represented in fig. 160.

The defect of this instrument is, that the current to be measured must remain constant during the time required to perform the adjustments, which is seldom the case.

269. *The Astatic Galvanometer* is used either simply as a galvanoscope, to discover the existence of a current, or as a measurer of the strengths of weak currents. When a needle is placed under a straight wire, through which a current passes, it deflects to a certain extent; and when the wire is bent, so as also to pass below the needle, it deflects still more. The current in the upper and the lower wire moves in opposite directions; and the deflection caused by both wires is in the same direction. By thus doubling the wire, we double the deflecting force. If the wire, instead of making only one such circuit round the needle, were to make two, the force would be again doubled, and if several,

the force (leaving out of account the weakening of the current caused by the additional length of the wire) would be increased in proportion. If the circuits of the wire be so multiplied as to form a coil, this force would be enormously increased. Two needles, as nearly the same as possible, placed parallel to each other, with their poles in opposite ways, as shewn in fig. 161, and suspended, so as to move freely, by a thread without twist, have little tendency to place themselves in the magnetic meridian, for the one would move in a contrary direction to the other. If they were exactly of the same power, they would remain indifferently in any position. They cannot, however, be so accurately paired as this, so that they always take up a fixed position, arising from the one being somewhat stronger than the other. This position is sometimes in the magnetic meridian, sometimes not, according as the needles are less or more perfectly matched, and their axes lie in the same vertical plane.

Fig. 160.

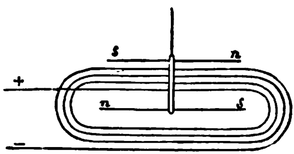


Fig. 161.

Such a compound needle is called *astatic* (Gr. *a*, privative, and *histamai*, I stand), as it stands apart from the directing magnetic influence of the earth. If an astatic needle be placed in a coil, as in fig. 162, so that the lower needle be within the coil and the upper one above it, its deflections will be more considerable than a simple needle, for two reasons: in the first place, the power which keeps the

needle in its fixed position is small, and the needle is consequently more easily influenced; in the second place, the force of the coil is exerted in the same direction on two needles instead of one, for the upper needle being much nearer the upper part of the coil than the lower, is deflected alone by it, and the deflection is in the same direction as that of the lower needle. An astatic needle so placed in a coil constitutes an astatic galvanometer. One of these instruments is shewn in fig. 162. Round an ivory bobbin, AB, a coil of fine copper wire, carefully insulated with silk, is wound, its ends being connected with the binding screws, *s*, *s′*. The astatic needle is placed in the bobbin, which is provided with a vertical slit to admit the lower needle, and a lateral slit to allow of its oscillations, and is suspended by a cocoon thread from a hook supported by a brass frame. The upper needle moves on a graduated circle; the compound needle hangs freely without touching the bobbin. The whole is included in a glass case, and rests on a stand, supported by three levelling screws. When used, the bobbin is turned round by the screw, Q, until the needle stands at the zero point, and the wires through which the current is sent are fixed to the binding screws. The number of degrees that the needle deflects may then be read off. It is manifest that on deflection taking place, the different portions of the coil are differently situated with respect to the needle from what they are at zero; the deflecting force of the coil, therefore, differs with the position of the needle, so that the angles of

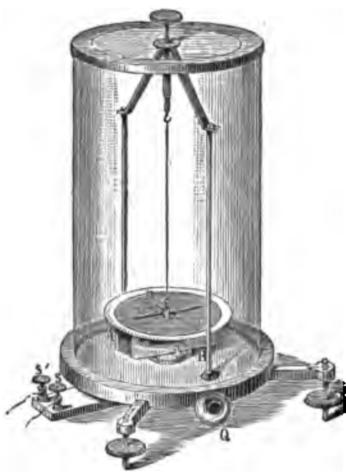


Fig. 162.

deflection or their functions are not proportional to the different current strengths. Up to from 15° to 20° it is found that, for most instruments, the current strength is proportional to the angle of deflection. Beyond that, the relations of strength indicated by different angles must be ascertained by special experiments.

270. *Thomson's Reflecting Galvanometer.*—This is by far the most sensitive galvanometer hitherto constructed. It consists of a coil of well-insulated wire, of which a section made by a plane through the axis of the coil is represented in fig. 163. In the centre of the coil is placed a small circular mirror made of the thinnest microscopic glass silverised. This mirror is suspended by a single cocoon fibre. The magnets, sometimes five in number, made of short lengths of the finest hair-spring, and magnetised to saturation, are cemented to the back of the mirror. The whole, magnets and mirror together, weighs less than a grain. The little mirror is usually suspended from the upper side of a cylindrical brass box, which fits into the hole of the coil, and which is closed in front by a lens, or a circle of glass. Fig. 164 represents the galvanometer, with its lamp and scale, as ready for use. The scale is placed about three or four feet from the mirror, with its zero point a little above the line of the axis of the coil. Below the zero point of the scale is a vertical rectangular slit, and close behind this is placed the clear flame of a paraffin lamp. Suppose the mirror stationary, and perpendicular to the axis of the coil. The ray of light from the lamp passing through the slit will then be reflected straight back, and form a bright spot of light on the zero point of the

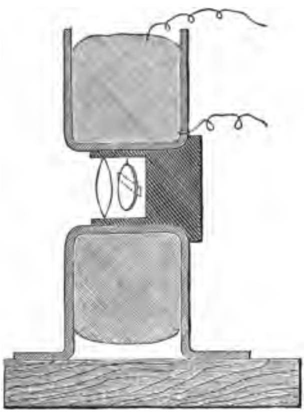


Fig. 163.

scale. When a current is now sent through the coil, the mirror will be deflected, and the spot of light will move towards the one or other end of the scale. According to the optical law of the reflection of light, the angle through

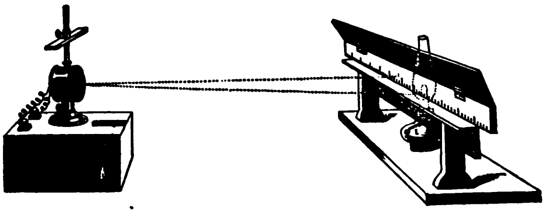


Fig. 164.

which the ray of light falling on the mirror is deflected, is double the angle through which the mirror is itself deflected; and this, combined with the long distance of the scale from the mirror, causes the spot of light to move over a long space for a very small deflection of the mirror. Hence the extreme sensitiveness of the instrument. As this galvanometer is very sensitive to even the faintest currents, it is extremely useful, and, in fact, universally employed for determining resistances by means of the *null method*, such as Wheatstone's Bridge, where the thing to be observed is the absence of any current.

CHAPTER XXI.

CURRENT INDUCTION.

271. *The fundamental fact* of current induction may be thus shewn. Two long copper wires, *pp* and *ss* (fig. 165), are fixed so as to be parallel and close to each other. The extremities of the one, *pp*, are in connection with the poles of a galvanic battery, E, and those of the other, *ss*, with the binding-screws of a galvanometer, G. The instant the circuit of the battery is completed, and the current sent along *pp*, a current in the opposite direction is induced in the wire *ss*, which is shewn by

the deflection of the needle of the galvanometer. This induced current is only momentary, for though the current continues to circulate in *pp*, the needle soon falls back to its original position of rest, and the wire *ss* gives free passage to other currents, and appears to be in no way affected. If, now, when the needle is at rest, the battery circuit be broken, and the current in *pp* stopped, another momentary current is indicated by the galvanometer needle, but in this case in the same direction as the inducing current. The inducing wire and current are called *primary*, and are so distinguished from the induced wire and current, which are termed *secondary*. The passive condition of the wire while thus under induction has been described by Faraday as *electro-tonic*. An electric throb, so to speak, marks the setting in of this state, and another its vanishing; the former in the opposite direction to that of the inducing current, and the latter in the same direction. If the primary wire, *pp*, be movable, so that it can be suddenly brought near to and withdrawn from the secondary *ss*, while the battery current passes steadily, currents are induced as in the former case, the approach of the wire being marked by an inverse current, and its withdrawal by a direct one. As long, however, as the primary wire remains in any one position, all evidence of electricity in the secondary wire disappears; but if in this position the strength of the primary current should be increased or diminished, momentary currents in the secondary wire would again mark the changes in the primary, the increase causing an inverse, and the decrease a direct current. Hence we conclude, that *a current which begins, a current which approaches, or a current which increases in strength, induces an inverse momentary current in a neighbouring conducting circuit;* and that *a current which stops, a current which retires, or a current which decreases in strength, induces a direct momentary current in a neighbouring circuit.* For inverse, the

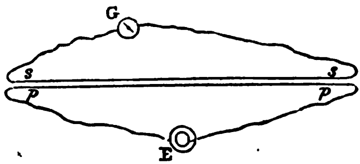


Fig. 165.

word *negative*, and for direct, the word *positive*, are frequently employed in reference to induced currents.

272. In experiments like the above, it is much more convenient to wind the primary and secondary wires side by side round a bobbin, so as to form a coil, as in fig. 166. The wires are insulated from each other by a covering of wool or silk. Not only does such a disposition admit of very long wires being used, but it also disposes the wires employed to greater advantage, for each single turn of the primary wire acts not only on the corresponding turn of the secondary wire, but on all the turns near it. The inductive effect of such a coil is much greater than that which would be obtained by the same extent of wires running side by side in a straight or crooked line. It is not even necessary that the two wires be wound round together; each may be wound on a separate bobbin, and the one placed inside the other as in fig. 167. The primary coil, P, here represented, is made of wire $\frac{1}{12}$th of an inch in diameter, covered with wool; and the secondary coil, S, of silk-covered wire, about $\frac{1}{80}$th of an inch, and much longer than the primary wire. With two such coils, the illustration of the preceding principles of induction can be conveniently given. If the primary coil be placed in the circuit of a galvanic cell, by two loose and flexible wires, so as to allow of its easy motion, and if the terminal binding-screws of the secondary coil be placed in connection with a galvanometer, when P is inserted into S, a momentary inverse current is indicated, and when it is removed, a momentary direct one; or if, when P remains in S, the strength of the primary current be altered, the needle announces the induction of currents according to the principles stated above. In order, however, to obtain the greatest effect from the secondary coil S, it is necessary, whilst P remains within it, to have some means of continuously completing and breaking the primary current. A contrivance

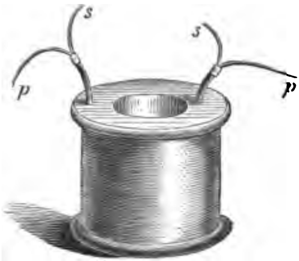


Fig. 166.

for this purpose is called a *current-break*. A simple current-break may be made of a common file, by holding one wire from the battery against the end of the file, and running the other along the teeth, the current being stopped each time the

Fig. 167.

wire leaves a tooth. In this way, a rapid series of interruptions is effected, each of which is attended by an inverse and a direct current in the secondary wire. A break of the same description, but more constant, may be also made by causing a metal spring to press against the teeth of a metal wheel, both spring and wheel being connected with the battery. As the wheel is turned by a handle, the spring breaks the contact each time it slips from one tooth to another. The most convenient form of break, however, is one which is made self-acting by the action of an electro-magnet, which receives the name of a *magnetic hammer*. One form of this instrument is shewn in fig. 272.

273. In any induction arrangement we can imagine the primary circuit replaced by its equivalent magnetic shell, and hence we are prepared to find that induced currents will be produced in a circuit by the motion of a magnet in its neighbourhood, or by in any way altering the strength of the magnetic field in which it is placed. This can be readily

shewn by experiment as follows: Place the coil S (fig. 167) in circuit with a galvanometer. Insert the north pole of a magnet into the axis of the coil, when a momentary induced current will be observed to pass through the galvanometer. Withdraw the pole, and a current will be observed in the opposite direction. Again, if we place a magnet in the axis of the coil, and alternately increase and diminish its magnetism by bringing first the north pole and then the south pole of another magnet up to its south pole, induced currents in opposite directions will be observed to pass through the galvanometer. In fact, the inductive action of a magnet upon any circuit is, in all cases, precisely equal to the inductive action of its equivalent electrical circuit upon the same.

274. *Mutual Induction and Self Induction.*—Suppose we have two circuits, A and B, it is found by experiment that the induction produced on B by a current, C, in A is equal to the induction produced on A by the same current, C, in B. This is shewn by first putting the current C in A, and the galvanometer in B, and then the current C in B, and the same galvanometer in A, when the electro-motive force of induction is found to be the same in the two cases. From this it follows that the number of lines of force inclosed by B, due to a current C in A, is equal to the number of lines of force inclosed by A, due to the same current, C, in B. Hence if the current strength in A be unity, and if M be the number of lines of force due to A inclosed by B, M will also be the number of lines of force inclosed by A due to unit-current in B. The quantity M is called the *coefficient of mutual induction* between the two circuits; and it can be shewn mathematically to be equal to the mutual potential of the one circuit on the other.

Since a circuit carrying a current acts inductively upon every neighbouring circuit, it follows naturally that it must also have a similar action upon the different parts of itself, seeing that these parts may be regarded merely as cases of very near neighbouring circuits. This is found to be actually the case; and the phenomenon has received the name of Self-Induction. The fact of self-induction was first made

known by Jenkin, who observed that a smart shock could be got from a single voltaic cell by breaking (but not by closing) the circuit, when an electro-magnet was included in the circuit, but that no appreciable shock was got when the electro-magnet was excluded. This observation was communicated to Faraday, who very soon traced it to its true cause in 'the induction of the current on itself.' Self-induction reveals the fact that, when a current circuit is closed, the current does not all at once reach its full strength, but takes some very short time to do so, and that during this time the current is retarded by the opposite current due to self-induction. Similarly, when the circuit is broken, the current strength does not fall to zero all at once, its gradual fall being prolonged by the current due to self-induction, which is, in this case, in the same direction as the main current. The currents due to self-induction are also called *extra currents.* Now, suppose we have a circuit, A, carrying a unit current, and that L is the number of lines of force inclosed by A due to self-induction, then L is called the *coefficient of self-induction.*

275. *Law of Current Induction.*—The fundamental law of induction has been deduced by Sir William Thomson and Helmholtz from the principle of the conservation of energy, in a way which may be understood from what follows. Suppose we have a circuit placed in a field of uniform magnetic force. Such a circuit may be represented by the

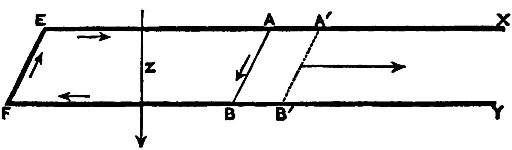


Fig. 168.

horizontal rectangle, ABFE (fig. 168), placed in the field of force due to the earth's magnetism, where EX and FY are supposed to be two parallel rails joined by the fixed cross-piece EF, and AB to be a movable wire which can slide along

the rails. Also, let the rails EX, FY, and the cross-piece EF, be of very thick wire, so that their resistance may be neglected; and let R be the resistance of the sliding piece AB. Let E be the electro-motive force in the direction of the arrows, and C the current in the circuit ABFE; and let Z represent the vertical component of the earth's magnetism. Then, according to sect. 249, the electro-magnetic force acting upon AB will tend to move it parallel to itself in the direction indicated by the arrow. Let AB move in the small time t into the position A′B′; and let N_1 represent the number of lines of force inclosed by the circuit at the beginning, and N_2 the number inclosed at the end of the motion. Then the work done by the electro-magnetic force during the small time t, is represented by $(N_2 - N_1)C$. The heat produced by the current in the time t is, by Joule's Law (sect. 226), RC^2t, and the energy drawn from the battery in the same time is ECt. But the total work done must be equal to the energy expended, and hence we have

$$ECt = RC^2t + (N_2 - N_1)\,C,$$

which gives
$$C = \frac{E}{R} - \frac{N_2 - N_1}{tR}.$$

Now, since the electro-motive force E can have any value we please, we may make it *zero;* and, if C′ be the resulting value of C, C′ will represent the induced current produced by the motion of AB across the vertical lines of force.

Hence
$$C' = -\frac{N_2 - N_1}{tR}.$$

From this we see that $-\dfrac{N_2 - N_1}{t}$ is the electro-motive force of induction. But $\dfrac{N_2 - N_1}{t}$ is the number of lines of force added to the circuit in a unit of time; and this taken negatively is also the rate of decrease in the number of lines of force passing through the circuit. Hence we have the following law as expressed by Clerk-Maxwell:

The total electro-motive force acting round a circuit at any instant, is measured by the rate of decrease of the number of lines of magnetic force which pass through it.

We can now find general expressions for the electro-motive force in each of two circuits acting inductively on each other. Let A and B be the two circuits, and let E be the electro-motive force, R the resistance, and C the current in A; and let E′, R′, and C′ be the same values for B. Also let L and N be the coefficients of self-induction of A and B respectively, and M the coefficient of mutual induction. The total number of lines of force inclosed by A will be the sum of those due to its own self-induction, and those due to B. Hence the value is LC + MC′. Similarly, the total number inclosed by B is NC′ + MC. By taking the rates of decrease of these quantities, we find the induced currents in A and B respectively, and hence we have

$$E - \text{rate of increase of } (LC + MC') = RC;$$
$$E' - \text{rate of increase of } (NC' + MC) = R'C'.$$

276. *Total Current of Induction.*—Since the electro-motive force of induction depends on the rate of decrease of the number of lines of force which pass through the circuit, it will only be constant when this decrease is constant—that is, when the same number of lines of force is abstracted from the circuit in each unit of time. Also, since the resistance of the circuit is always the same, the induced current will only be constant under the same circumstances. In all other cases the current induced in the secondary circuit by the motion of a magnet or primary circuit in its neighbourhood, will continually vary; and hence, to find the *total induced current*—that is, the whole quantity of electricity conveyed by the induced current, we must sum up all the quantities of electricity conveyed by it during each small element of the time of the motion to which it is due. In order to do so, we proceed as follows: Let the whole time of the motion be divided into a very large number, n, of very small portions, t, each so small that the current during it may be supposed constant. Let N_0 be the number of lines of force inclosed by the circuit at the commencement of the motion; N_1 the number inclosed at the end of the first or beginning of the second small time, t; N_2 the number inclosed at the end of the second or beginning of the third, and so on; N_n being

the number inclosed at the end of the motion. Also, let C_1 be the current, and Q_1 the total current of induction, during the first small portion of time, C_2 and Q_2 the same quantities for the second, and so on. From equation (sect. 275) we have:

$$C_1 = -\frac{N_1 - N_0}{tR}.$$

But the total quantity of electricity conveyed by a constant current, C_1, in the time t is $C_1 t$.

Hence, $$Q_1 = C_1 t = -\frac{N_1 - N_0}{R}.$$

Similarly, $$Q_2 = C_2 t = -\frac{N_2 - N_1}{R}.$$

. . . .

$$Q_n = C_n t = -\frac{N_n - N_{n-1}}{R}.$$

To find the total current of induction, which we denote by Q_i, we must sum up all these quantities. Hence we have:

$$Q_i = -\frac{1}{R}(N_1 - N_0 + N_2 - N_1 \ldots\ldots + N_n - N_{n-1})$$

$$= -\frac{1}{R}(N_n - N_0) = -\frac{\text{Total number of lines of force added}}{R}.$$

An example or two of the application of this result to simple cases will help to make the subject clear; and first let us take the case of the parallel slider represented in fig. 168. Let AB move parallel to itself into the position A′B′, in the time t; and let the distance BB′ equal x. The number of lines of force inclosed by the circuit at the beginning of the motion is equal to Z × the area ABFE; and the number inclosed at the end is Z × the area A′B′FE. Hence the number of lines of force added to the circuit is the difference of those two quantities—that is, is equal to Z × area AA′B′B. Denoting the length of AB by l, we have for E_i, the electromotive force of induction, provided the motion of AB be uniform, the value,

$$E_i = -\frac{Zlx}{t}. \qquad (1)$$

Now, $\frac{x}{t}$ is clearly the velocity of AB. Denoting it by v, we have $E_i = -Zlv$. Hence the electro-motive force of induction is proportional to the velocity.

Also, for Q_i, the total current of induction, we have :

$$Q_i = -\frac{Zlx}{R}. \qquad (2)$$

It is important to notice the direction of the induced current. Since the direction of the lines of force is downwards, the positive direction round the circuit, according to the corkscrew rule, is ABFE. Hence, since the value of E_i is negative, the direction of the induced current is opposite to this—that is, is in the direction EFBA. Had AB moved in the opposite direction, the direction of the induced current would have been positive. Hence we see that when the lines of force are increasing, the direction of the induced current is negative, and when decreasing, positive.

As another example, we shall find the value of the total current of induction in a circular circuit due to the motion of a magnet-pole along its axis.

Let ABC (fig. 169) be the circular circuit, EF its axis ; and let a magnet-pole of strength m be moved towards the circuit

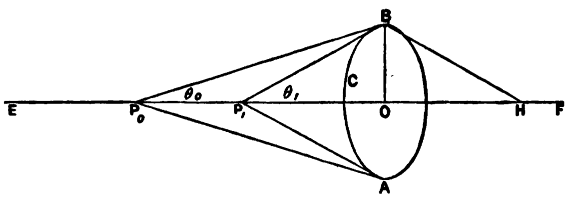


Fig. 169.

from the point P_0 to the point P_1. The length of the magnet is supposed to be so great that its south pole is at an infinite distance, and has no action upon the circuit. Now, let V_0 and V_1 be the potentials in reference to the circuit of a unit-pole placed at P_0 and P_1 respectively. Then the number of lines of force inclosed by the circuit at the commencement

of the motion is mV_0, and at the end, mV_1. Hence, the total current of induction,

$$Q_1 = -\frac{m}{R}(V_1 - V_0).$$

Now, V_0 is the value of the solid angle subtended by the circuit at the point P_0; that is, is equal to the area on a unit-sphere having P_0 for its centre, cut off by a cone which has P_0 for its vertex, and the circuit ABC for its base. The determination of this area is a subject for pure mathematics, and is equal to $2\pi(1 - \cos\theta_0)$, where θ_0 is the angle BPO. Hence $V_0 = 2\pi(1 - \cos\theta_0)$. Similarly, $V_1 = 2\pi(1 - \cos\theta_1)$, where θ_1 is the angle BP_1O. Hence we have

$$Q_1 = -\frac{m}{R}\{2\pi(1 - \cos\theta_1) - 2\pi(1 - \cos\theta_0)\}$$

$$= -\frac{2\pi m}{R}(\cos\theta_0 - \cos\theta_1). \qquad (3)$$

Several instructive deductions can be drawn from this result.

(1) Suppose the pole, m, to be suddenly placed at the point P_1. This is the same as supposing the point P_0 to be at an infinite distance to the left of the circuit, and that the pole, m, is gradually moved up from this distance to the point P_1. But when P_0 is at an infinite distance, $\theta_0 = O$, and $\cos\theta_0 = 1$.

Hence, $$Q_1 = -\frac{2\pi m}{R}(1 - \cos\theta_1).$$

(2) Suppose the pole, m, to be suddenly placed at the centre of the circuit O, then $\theta_1 = 90°$, and $\cos\theta_1 = O$.

Hence, $$Q_1 = -\frac{2\pi m}{R}.$$

(3) Suppose the pole, m, to be passed along the axis, through the circuit, from an infinite distance on the left to a point, H, on the right, such that $OH = OP_1$. Then

$$Q_1 = -\frac{2\pi m}{R}(1 - \cos BHF) = -\frac{2\pi m}{R}(1 + \cos\theta_1).$$

(4) Suppose the pole, m, to be passed through the circuit

from an infinite distance to the left to an infinite distance to the right of the circuit. Since, in this case, θ_1 becomes 2π, and $\cos\theta_1 = 1$, we have:

$$Q_1 = -\frac{2\pi m}{R}(1+1) = -\frac{4\pi m}{R}.$$

277. *Properties of the Induced Current.*—The following properties of the induced current have been experimentally observed: they can also be deduced from the general law above given.

(1) The total quantity of electricity conveyed by the induced current at closing the primary circuit, is equal to the total quantity conveyed by the induced current at breaking the primary circuit. Faraday proved this by placing a delicate galvanometer in the secondary circuit, and making and breaking contact very rapidly in the primary circuit. No permanent deflection of the galvanometer needle was observed, which shewed that the jerk given to the needle in one direction by the induced current at make, was exactly counterbalanced by the jerk given in the opposite direction by the induced current at break. Hence the quantities of electricity conveyed by the two currents in opposite directions must have been equal.

(2) The induced current is independent of the material of which the circuit is composed. To shew this, Faraday twisted together two insulated wires of different materials, but having the same electrical resistance. The wires were soldered together at one end, and the free ends attached to the terminals of a galvanometer. No deflection was produced when the twisted portion was moved rapidly in the magnetic field produced by a powerful electro-magnet, which shews that the induced current in both wires was the same.

(3) The strength of the induced current is proportional to the strength of the inducing current. This follows at once from the general law, and admits of easy experimental proof by the galvanometer. If the primary circuit consists of n coils of wire each carrying the current C, the induced current is proportional to nC.

(4) The induction in a coil of m windings produced by a

coil of n windings is proportional to the product mn. This also follows from the general law.

278. *Lenz's Law.*—Lenz's law is thus expressed by Clerk-Maxwell:

If a constant current flows in a primary circuit A, and if, by the motion of A, or of the secondary circuit B, a current is induced in B, the direction of this induced current will be such that, by its electro-magnetic action on A, it tends to oppose the relative motion of the circuits.

A single example will illustrate the law. Let A and B (fig. 170) be two straight parallel circuits, A being the primary, and B the secondary; and let the current in A be in the direction of the arrow. It will be remembered that the lines of force due to the long straight current A are concentric circles surrounding it. A number of these lines of force will be inclosed by the secondary circuit B. Now, let A be moved parallel to itself towards B. The number of lines of force inclosed by B will be increased by this motion, and, in consequence, an induced current will be produced in B in the direction of the arrow—that is, in the opposite direction to the current in A. Now we have here two parallel currents in opposite directions, which we know (sect. 250) repel each other. Hence the electro-magnetic action between A and B opposes the motion which produces the induced current in B.

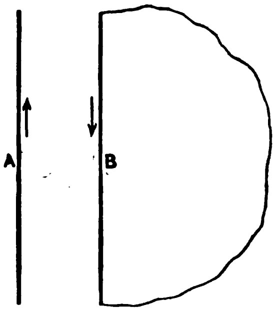


Fig. 170.

Neumann made Lenz's law the foundation of his mathematical theory of induction. From it, along with Ampère's expression for the force between the elements of two currents, he deduced, in mathematical form the law of electro-magnetic induction.

279. *Self-Induction, Extra-Current.*—These have already been shortly alluded to. Suppose we have a single circuit, and let us suppose it placed in a magnetic field of zero

intensity. Let the electro-motive force acting in the circuit be E, and the resistance R. Then, according to Ohm's law, the *steady* current in the circuit is $C = \frac{E}{R}$. On closing the circuit, the current does not increase from zero to its steady value all at once, but takes some time to do so, during which it is gradually increasing. During this time the number of lines of force passing through the circuit is also gradually increasing, and, in consequence, an electro-motive force of induction, E′, acts round the circuit in the opposite direction to E, tending to hinder the current attaining its steady value. Now, according to our general law, the value of E′ at any time is measured by the rate of decrease of the number of lines of force passing through the circuit—that is, it is equal to the negative value of the rate of increase of the number of lines of force passing through the circuit. Now, if C′ be the current at the time when the electro-motive force is E, and if L be the coefficient of self-induction, the number of lines of force passing through the circuit at that time is LC′. Hence we have for the current at any time the expression

$$C' = \frac{E}{R} - \frac{\text{rate of increase of } LC'}{R}.$$

The second term on the right-hand side of this equation represents the induced current at the time mentioned. It will become zero, of course, when the current reaches its steady value C, since then the rate of increase of the constant quantity LC is zero. To find the total current of self-induction, we proceed exactly as in the corresponding problem for mutual induction (sect. 276). Denoting it by S_i, when S_i is the total current of self-induction due to closing the circuit, we have

$$S_i = -\frac{\text{number of lines of force added}}{R}. \qquad (1)$$

But at closing, the number of lines of force included in the circuit is O, and when the current has become steady the number included is LC. Hence

$$S_i = -\frac{LC - O}{R} = -\frac{LC}{R} = -\frac{L}{R} \cdot \frac{E}{R} = -\frac{LE}{R^2}. \qquad (2)$$

Next let the circuit be broken after the current has attained its steady value. The current will not fall to zero all at once, but will take some time to do so. During this time the number of lines of force passing through the circuit is gradually decreasing, and, in consequence, an electromotive force of induction acts round the circuit in the same direction as that of the primary current, tending to hinder the stopping of the current. Proceeding as before, we find the same equation (1) for the total current of self-induction at break. We must remember, however, that in order to get the 'number of lines of force added,' we must in all cases subtract the number inclosed at the beginning from the number inclosed at the end. Now, at breaking the circuit, the number inclosed at the beginning is LC, and at the end O. Hence the number of lines of force added is O — LC. Calling B_t the total current of self-induction at break, we have

$$B_t = -\frac{O - LC}{R} = +\frac{LC}{R} = +\frac{LE}{R^2}. \qquad (3)$$

The currents due to self-induction are sometimes called *extra-currents*; and from equations (2) and (3), we see that the extra-currents at make and break are equal in quantity, but opposite in direction.

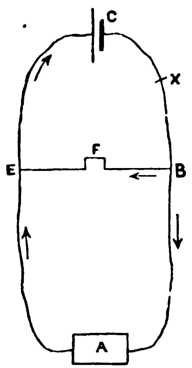


Fig. 171.

The properties of the currents due to self-induction are the same as those of the currents due to mutual induction. They are, for instance, independent of the material of which the circuit is made, and are also directly proportional to the strength of the inducing current.

280. *Illustrations of Self-Induction.*—Self-induction can be illustrated experimentally in a variety of ways, of which the following are examples. Let C be a single voltaic cell (fig. 171), having in circuit the coil A, whose self-induction is to be observed. Let BE be a cross circuit, having a gap at F,

into which a wire or galvanometer can be inserted. Also let X be a make-and-break whereby the current can be rapidly interrupted. When the circuit is closed, part of the current goes through the branch circuit BE, and part through the coil A. Now let a fine platinum wire be inserted at F, and let its resistance be so adjusted that it does not glow by the passing of the steady current through it. Let the circuit be now broken at X. The current due to the self-induction of A cannot pass through the battery, but must all pass through EB in the direction BAEB. This is shewn by the wire at F commencing to glow directly the circuit is broken. Faraday has also shewn, by a similar experiment, that the electrolysis of water can be produced by a single cell, provided the direct current, and the current due to the self-induction of A, be simultaneously sent in the same direction through a voltameter. To shew this experiment, the coil A is placed at X, the voltameter at A, and the make-and-break at F.

281. *Two circular Coaxial Solenoids with Iron Core in the primary circuit.*—Let A and B be two circular coaxial solenoids—A being the primary and B the secondary circuit. It is found that the induction produced in B by the making and breaking of a current in A is greatly increased by inserting an iron core in A. The reason of this is obvious from sect. 264, which shews that the number of lines of force which pass through A is greatly increased by the insertion of the iron core.

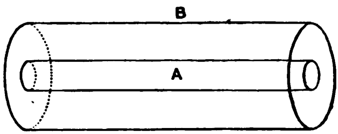


Fig. 172.

Let l be the length of each of the solenoids A and B. Let n be the number of windings per unit-length of A, and n' the number of windings per unit-length of B. Also let R be the resistance of A, and S the resistance of B; and let L and N be the coefficients of self-induction of A and B respectively, and M the coefficient of their mutual induction. If the length of A be great in comparison with its diameter, the magnetic field within A, produced by a current circulating in

it, is very nearly uniform; and for a unit-current in A, the strength of this field at any point is (sect. 262. 3) equal to $4\pi n$. Hence, if a be the area of the cross section of A, the number of lines of force due to a unit-current inclosed by A is $4\pi na$. But this is also the number of lines of force inclosed by each winding of B. But the number of windings in B is ln'. Hence the number of lines of force inclosed by all the windings of B is $4\pi nln'a$. Now the number of lines of force inclosed by B, due to unit-current in A, is by definition (sect. 274) the coefficient of mutual induction between them. Hence $M = 4\pi nln'a$. By inserting an iron rod of cross section a' in A, the number of lines of force which pass through A becomes (sect. 264) $4\pi n\ (a + 4\pi ka')$, and hence the value of M becomes $M' = 4\pi nln'\ (a + 4\pi ka')$, where k is the coefficient of magnetic induction of the iron rod.

Now let E be the electro-motive force, and C the steady current in A, and let t be the very small time which elapses between the instant of closing the circuit and the instant when the current becomes steady. The total current of induction Q_i in B is given by sect. 276, and is, at make,

$$Q_i = -\frac{\text{number of lines of force added}}{S}$$
$$= -\frac{MC}{S} = -\frac{ME}{SR}.$$

Similarly at break, the total current of induction Q_i' is

$$Q_i' = +\frac{ME}{SR}.$$

This shews that the total quantities of electricity conveyed by the induced currents at make and break are equal.

Again, let E′ be the average electro-motive force, and C′ the average strength of the induced current during the time t.

Then $$C' = \frac{E'}{S};$$

but evidently $$Q_i = C't.$$

Therefore $$C't = -\frac{ME}{SR};$$

hence $$C' = -\frac{ME}{SRt}.$$

Therefore $$\frac{E'}{S} = -\frac{ME}{SRt};$$

which gives $$E' = -\frac{M}{Rt}\cdot E.$$

Now, since t is a very small fraction of a second, this shews that the electro-motive force of induction may be a large number of times greater than the electro-motive force of the battery; and this accounts for the very great length of spark got between the terminals of the induced circuit, in comparison with the very short spark got at closing and opening the primary circuit. According to Sir William Thomson, it would require 5510 Daniell's cells to produce a spark $\frac{1}{8}$th inch long between two brass terminals, and yet a spark many times that length can be got from an induced current by using even a very few cells in the primary circuit. We shall find great use for this result in explaining the induction coil.

From the above equation, $M = 4\pi n l n' a$, we can easily find the value of L. All we have to do is to make $n = n'$, and then suppose the coil B to contract till it coincides with A. The two coils may be then regarded as one, which of course can only have self-induction. We have thus

$$L = 4\pi l n^2 a.$$

Similarly, by supposing a coil of n' windings per unit-length exterior to B, and then letting the coils coincide, we obtain

$$N = 4\pi l n'^2 b,$$

where b is the sectional area of B.

282. *Electricity induced by the Magnetism of the Earth.*—Faraday was the first (1831) to obtain electricity from the inductive action of terrestrial magnetism. Terrestrial electric induction may be shewn by such an apparatus as that sketched in fig. 173. If a coil, CC′, be made to rotate, as shewn in the figure, round a horizontal axis, and its ends be directly connected with a galvanometer, it will be found that, starting from a certain position, for one half-revolution the needle is deflected one way, and for the other in the opposite way. Suppose the axis to lie at right angles to the magnetic meridian, and that we place the plane of the coil at

right angles to the dipping-needle, as a starting-point, each half-revolution will occasion a current in an opposite direction. The reason of this is obvious. Through the half-revolution one half of the coil ascends and the other descends, cutting the lines of magnetic force, which are parallel to the dipping-needle in different ways; opposite currents are thus induced in each half, and these aid each other to form one current.

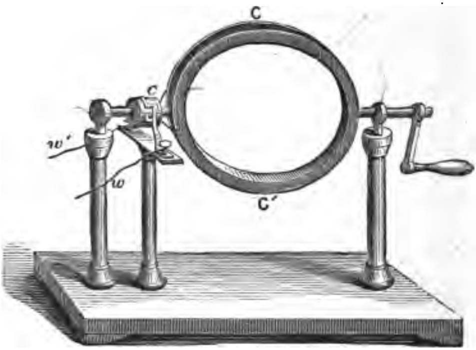


Fig. 173.

The descending half has its current tending eastward, and the ascending half westward. It is easy to see that by the intervention of a commutator, as at *c*, a current in one direction may be obtained through the wires *w*, *w'*. The maximum induction takes place when the plane of the coil is parallel to the dipping-needle, for then it cuts the lines of magnetic force at right angles. If the axis of the coil be placed horizontally in the magnetic meridian, the induced electricity will be wholly due to the vertical magnetic lines. If the axis be vertical, the same will be due wholly to the horizontal lines. A comparison of the deflection produced on the galvanometer by a similar rotation in these two positions may be used, according to Weber's suggestion, to determine the magnetic inclination, for the tangent of the angle of inclination is equal to the vertical divided by the horizontal intensity. If the axis be parallel to the dipping-needle, no current will be obtained, however fast the rotation. Palmieri, by means

of a terrestrial induction machine, produced sparks, shocks, and the decomposition of water.

283. *Induced Currents of Higher Orders.*—Suppose we have a set of circuits A, B, C, D, &c., B being under the inductive influence of A, C under the inductive influence of B, D under C, and so on. Also suppose a direct primary current be sent for a moment through A; this will cause an *inverse* and *direct* induced current of the first order in B. Now, the inverse current in B will cause a direct and inverse induced current in C; and the direct current in B will cause an inverse and direct current in C. Similarly the direct and inverse currents in C will cause corresponding currents in D, and so on. Thus from the interruption of one current in A, two currents are produced in B, four in C, eight in D, and so on, increasing in geometrical progression. These are called the *induced currents of higher orders.* As might be expected, they diminish very rapidly in intensity; but their presence has been detected by their physiological action and otherwise.

284. *Unipolar Induction.*—This is the name given to a class of phenomena which may be regarded as the converse of the electro-magnetic rotations already alluded to (sect. 259). An example will make the meaning of the term clear.

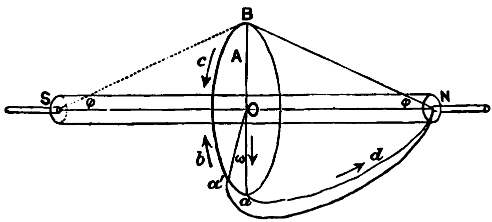


Fig. 174.

Let SN be a cylindrical straight magnet supported on pivots at the ends S and N, so that it can rotate round its axis. Also let A be a circular disc of copper attached to the middle point of the length of the magnet, so that its plane is perpendicular to the axis of the magnet which passes through its centre. Let *ad*N be a conducting circuit attached to the

pivot at N, and having sliding contact with the copper disc at *a*. Now, if the current from a cell be sent through the circuit O*ad*N in the direction of the arrows, its electro-magnetic action will cause the magnet and disc to rotate in the direction of the arrow *b*. And, conversely, if the magnet and disc be rotated in the opposite direction, that is, in the direction of the arrow *c*, an induced current will be produced in the circuit in the same direction as before, namely, O*ad*N. This is the phenomenon called, rather unfortunately, *unipolar induction*.

To find the electro-motive force of the induced current, we proceed as follows. Instead of making the disc A rotate in the direction of the arrow *c*, we may obviously suppose the disc stationary, and that the circuit N*da* with the sliding contact revolves with the same angular velocity in the opposite direction. This will clearly produce the same effect. Now suppose the radius O*a*, carrying the end of the circuit with it, to revolve in a unit of time from the position O*a* to the position O*a′* through the angle ω. Then ω is the angular velocity, and we have to find the electro-motive force due to this motion. The whole number of lines of force inclosed by the circumference of the disc A is $4\pi m \cos\phi$, where m is the strength of the magnet-pole, and ϕ is the angle BNO = BSO. The number of lines of force cut through by the radius O*a* in its motion to O*a′* is clearly the number included in the sector *a*O*a′*. But this number is the same fraction of the whole number that ω is of two right angles, that is, of 2π. Hence the number cut through by O*a* in a unit of time is $\frac{\omega}{2\pi} \times 4\pi m \cos\phi = 2\, m\omega \cos\phi$.

But this is the electro-motive force of induction without regard to sign. Therefore calling it E′, we have E′ $= 2m\omega \cos\phi$.

To get the whole current produced by one revolution of the disc, we must substitute 2π for ω in the above, and divide by the resistance, R, of the circuit. Hence we have for the total current of induction, due to one revolution, the value $\frac{4\pi m \cos\phi}{R}$.

The direction of the induced current is most easily obtained, in any case, by the application of Lenz's law. Observing that the lines of magnetic force go through the disc from S to N, and applying the rule given in sect. 249, we see that the induced current in Oa must be from O to a, in order that it may, by its electro-magnetic action, oppose the motion of Oa into the position Oa'. Hence the direction of the induced current is as indicated.

CHAPTER XXII.

ELECTRO-MAGNETIC AND MAGNETO-ELECTRIC INDUCTION APPARATUS.

285. Since the discovery of current induction by Faraday, a great variety of apparatus has been constructed whereby electric currents can be produced by means of induction. The various kinds of this apparatus can be divided into two great classes—first, those in which the induced current is produced by varying the strength of the magnetic field in which the circuit is placed; and secondly, those in which mechanical work is employed to rotate a coil of wire in a strong magnetic field. An example of the first class is the Induction Coil. Examples of the second are the various machines by means of which mechanical work is converted into the energy of the electric current. These machines will be described in a future chapter.

286. *Induction Coil.*—The essential parts of this apparatus have been already described. A primary coil with its core of iron wire, and a secondary coil exterior to, and insulated from the primary coil, form the main portions of the instrument. The primary coil is connected with the poles of a galvanic battery, and in the circuit a make-and-break is introduced, to effect the interruptions of the current essential to its inductive action. A commutator and condenser are also essential parts connected with the primary circuit.

The make-and-break is shewn in fig. 175. A is an iron

plate, into which the ends of the iron wires forming the core are fixed, and which serves as an anvil for the hammer H. H has for its shaft the stiff spring D, which keeps *p* back, and also forms part of the primary circuit. *p* is a little projecting nipple tipped with platinum, *e* is a screw, the end, *p′*, of which is also tipped with platinum. C, an upright brass standard, also forms part of the circuit. When the circuit is closed, A becomes magnetic, and draws away H from *p′*. The primary circuit formerly closed at *p* and *p′* is now broken. A loses its magnetism, and H, under the influence of the spring D, is taken back to *p′*. The circuit is again closed, A again becomes magnetic, and thus H is kept oscillating with great rapidity between A and *p′*, alternately opening and closing the primary circuit. *b* is a screw giving to D the necessary stiffness.

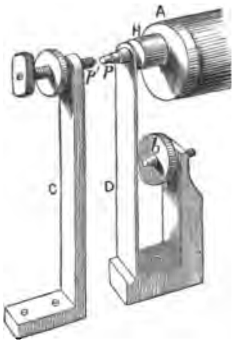


Fig. 175.

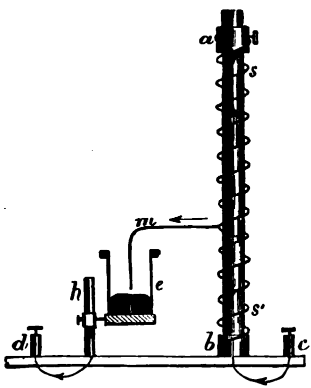


Fig. 176.

For large coils, mercury-breaks are almost always employed. A wire is made to dip into a cup of mercury and lifted out alternately, so as to make and break contact in the primary circuit. The interruption thus made is much improved by pouring alcohol over the mercury ; the spark of the extra-current taking place with more difficulty in alcohol than in air. As pure mercury, when thus used, is apt to be broken up into globules under the constant motion,

an amalgam of silver or platinum, of a treacly consistence, is substituted with advantage. The mercury-break, sketched in fig. 176, works with singular steadiness and efficiency. A spiral, *ss'*, of No. 13 copper-wire, made of about an inch in diameter, and six inches in length, is stretched out to about nine inches, and soldered to two rings on the rod *p*, half an inch in diameter. To shew the construction more clearly, the convolutions are shewn few and far apart. In the apparatus itself the spiral hides almost entirely the rod beneath. The rings being wider than the rod, keep the spiral free from it. The lower ring, *b*, is insulated from the rod; the other, *a*, being fixed by a binding-screw to it, is in conducting connection with it. The rod is partly of iron, partly of brass, and communicates with the binding-screw, *c*. A wire, *m*, is soldered to one of the convolutions a little above the end of the iron part of the rod, and comes out at right angles. It is turned down at the end, so as to dip into a cup of mercury, *e*, which communicates by the pillar, *h*, with the binding-screw, *d*. The break is on a separate stand from the coil, and is so placed in the primary-circuit that each binding-screw is connected with a coating of the condenser. When the commutator turns the current on, the spiral is gently moved by the hand, and if the wire dips into the mercury, continues in constant oscillation. The cup is raised or lowered till the point is got where the best sparks pass between the terminals of the coil, and fixed there with a binding-screw. A spiral, so hung, forms a delicate pendulum, which only requires a small force to keep it in steady motion up and down. This the electric and magnetic action supplies. When the current passes, it goes from *c* up the rod, down the upper part of the spiral into the cup, and thence to the binding-screw, *d*. The iron rod becomes magnetic, and tends to send the various convolutions at right angles to the lines of magnetic force. Moreover, the various convolutions are the seat of a current moving in the same direction in all, and they consequently attract each other. Under this double action, the dipping-wire is lifted out of the mercury, and its own elasticity brings it back, again to complete the circuit, again to be lifted out, and so forth. A

reversal of the current causing a reversal of poles, the action of the spiral is indifferent to the direction of the current. To prevent oxidation, the part of the wire that dips should be of platinum. The alcohol on the surface must be more than an inch deep, otherwise it is scattered about in all directions by the breaking spark. If not, the vessel must be closed with a lid.

The *commutator* consists of a cylinder of ivory, with two brass plates attached to its sides, moving on a brass axis, supported by two brass standards. One axis does not go through the whole way, so that two distinct pieces of brass serve as an axis. One of the standards is connected with the +, the other with the — pole of the battery. Each plate communicates with one of the standards, so that the plates form the poles. A spring presses against the cylinder, either on the plates or on the ivory. These springs form part of the circuit: when the springs press against the plates, the current flows; when the plates are reversed by a handle attached to the cylinder, the current is reversed.

The *condenser* consists of several sheets of tinfoil and oiled silk, laid alternately the one above the other. The first, third, fifth, &c. sheets of tinfoil are connected by strips of the same material; so are the second, fourth, sixth, &c.; the whole forming a condensing apparatus like a Leyden jar, the odd sheets forming the one coating, and the even sheets the other. Each set of sheets is connected with one of the wires of the primary coil. The condenser is generally placed in the sole of the instrument, and does not meet the eye.

An induction coil, as constructed by Ladd of London, is represented in fig. 177. The forms under which the instrument appears are very various, and the one in the figure only serves to shew the general requirements in its construction. The two binding-screws, *p* and *n*, are for the battery wires; C is the commutator. The two coils, W, lie horizontally on the sole of the instrument, S. The secondary coil alone is seen, the primary being within it and out of view. The breaking hammer, being behind the coil, is likewise not shewn. The condenser is contained by the box which constitutes the sole, and a conducting connection is established

between its coatings and the wires of the primary coil. The terminations of the secondary coil are fixed to the heads of the glass pillars, P, P′, which are furnished with pointed rods

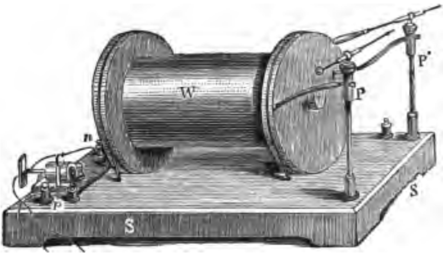


Fig. 177.

capable of universal motion. The excellence of the instrument depends on the proper insulation of the secondary coil. The bobbin must be made of glass, gutta-percha, or (best of all) vulcanite, so as to prevent the induced electricity from reaching the ground by the primary coil. Care must also be taken to insulate the different parts of the secondary coil from each other. If this were not done, the spark which completes the secondary current, instead of taking place at the rods, the place at which it is wanted, would pass within the coil itself. It is necessary, in consequence, to have each layer of the coil insulated from the other, by interposing gutta-percha paper, and cementing it with a hot iron to the sides of the bobbin. The induced current must thus pass through all the turns of the wire, and is prevented from shortening its course by leaping over one or more layers of the coil.

287. In the ordinary construction the wire is coiled first round the centre of the bobbin all the way along, and layer after layer is put in regular succession, the one above the other, with insulating material between. In this way the greatest difference of potential is between the inside and the outside layers, the poles coming directly from them. In this arrangement it is extremely difficult to maintain proper insulation. The utmost care is needed to keep the electricity

of the inmost layer of wire from leaping into the primary coil, and even when this is fully accomplished, there is a Leyden-jar action between the inmost layer of the secondary and the outmost layer of the primary coil, which hinders the free delivery of the electricity at its pole with which it is charged. We shall mention two ways of obviating this defect.

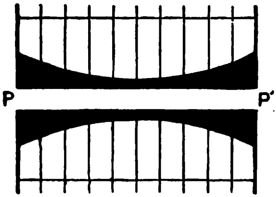


Fig. 178.

Fig. 178 is intended to shew the construction of the coil devised by Siemens and Halske. PP′ is the hollow tube in which the primary coil is put. The bobbin is made of ebonite, and the central part is thickest at the ends and thinnest at the middle, being 26 millimetres at the ends and 12 at the centre. It is 95 centimetres in length. To this tube are cemented 150 thin discs (only a few are given in the figure) of ebonite at equal distances, dividing the whole length into compartments. Each compartment is filled up with copper wire ·14 of a millimetre thick, covered with silk and varnished. The various compartments communicate with each other, so that the whole wire is continuous from end to end. The length of the whole is 129,000 metres. The silk and varnish on the wire are sufficient insulation between the convolutions in each compartment, and the discs are proof against the spark striking through between them. The insulation of the various parts from each other is thus complete. As regards external insulation, least is required for the middle compartments, where there is least danger of the electricity breaking through into the primary coil. Accordingly, the tube is thinnest at the middle, and thickest at the ends. The thickness at the ends not only prevents the electricity striking through, but lessens the Leyden-jar action between the ends and the primary coil. With one Bunsen cell this coil gives a spark of 21 centimetres; with six cells, one of 58 centimetres in length.

The section of the bobbin of a secondary coil (17 inches in length), of much smaller size and of a less expensive

character, is given in fig. 179. The coil of which it forms a part was made under the direction of Dr Ferguson. The central tube, PP′, is of hardened wood; *d*, D, and *d′* are thick discs of gutta-percha cemented to the tube. The wire is coiled in two portions, beginning at the middle, *m*; the one half being coiled to the right, the other to the left. If the whole could be seen, it would look like one coil from end to end with a disc in the middle. The two halves communicate by a wire piercing the central disc at *m*. Gutta-percha paper is wrapped round the tube to a thickness of more than a quarter of an inch before the wire is wound on. Each consecutive layer of wire (copper covered with silk) is separated from the one above or below by two or three sheets of gutta-percha paper. The coil has the greatest thickness at the middle, and tapers off to the ends. This is done in conformity with a principle discovered by Jacobi and Lenz (1844), namely, that in an electro-magnet, where the wire is uniformly distributed over its length, the inductive power is greatest at the centre, and becomes feeble at the ends. It is sought in this coil to proportion (approximately) the length of the wire coiled in different parts of the bobbin to the electro-motive force of the primary coil at that part. The sparks given off by this coil, which are nearly seven inches in length (with six Bunsen cells), are peculiarly dense, the quality aimed at in the construction. The length of the wire is about seven miles. The double form of the bobbin throws the middle of the wire next the primary coil. Here the potential being least, there is little or no danger of the electricity sparking into the primary coil. As the wire leaves the centre the potential increases, but the insulation from the additional sheets of gutta-percha paper between the different layers is also increased. The electricities of the poles are kept from uniting by the thick central disc (1 inch thick and extending 1½ inches beyond

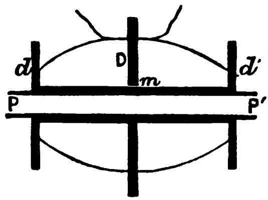


Fig. 179.

the coil), and a considerable thickness of gutta-percha placed over them. Within the coil they are kept apart by all the gutta-percha paper on each half of it. To prevent the gutta-percha from altering in the presence of the air, which it usually does, the whole is inclosed in a layer of melted paraffin.

288. *Experiments with the Induction Coil.*—Say that we experiment with a coil like the one shewn in fig. 177, about one foot long and nearly six inches in diameter, which yields readily sparks of from four to five inches with a battery of six Bunsen cells. After connecting the battery wires, and setting the commutator so as to complete the contact, let us place the movable rods within an inch of each other. An uninterrupted rush of sparks is transmitted between the points of the rods. The sparks are not the clear single sparks of the electric machine, but seem to be made up of several sparks occurring at the same instant, which are white and crooked. These are enveloped in a luminous haze, or aureole, which can be blown away by the breath, and thereby separated from the white spark, which cannot be so removed. The aureole is repelled by the poles of a powerful electro-magnet, whilst the white spark is not affected by it. As the rods are withdrawn from each other, it disappears, and when they stand above three inches apart, the spark resembles in every respect the forked single spark of a powerful electric machine. When the points are withdrawn beyond striking distance, electric brushes still play between them, which become visible in a darkened room. If the hand be brought near the rod connected with the exterior end of the coil, sharp stinging sparks, two or three inches in length, are got. The rod connected with the inner end does not yield them so readily, and this is the same whether it be the + or − pole. Each pole of the induction coil is the seat of two opposite electricities, alike in quantity, alternating with each other. A Leyden jar may be charged, but not to the same extent as by the electric machine, if one of the wires be connected with the outer coating, and the other brought within an inch of the knob. The jar on being removed may be discharged by the tongs. When the poles are put in connection with

the coatings of a Leyden jar, and the points placed within half an inch of each other, the sparks passing between the points are much more brilliant, and the sharp snap of the simple spark grows into a loud report. The Leyden jar effects a condensation of the electricity of each direct current, and each spark discharge takes place in shorter time, and consequently with greater intensity. The *condensed spark* punctures paper and the like with great facility, but it is of very low heating power. The uncondensed spark, more particularly the hazy spark, got when the poles are near each other, kindles paper, gunpowder, coal-gas, and other combustibles, with great readiness. The power of the direct induced current of even large induction coils to deflect the magnetic needle, and to effect chemical decomposition, is very insignificant. This shews that it is very much inferior to the inducing current in quantity, however much it may be superior in electro-motive force. The physiological effect, on the other hand, is tremendous, and the experimenter must take care not to allow any part of his body to form the medium of communication between the poles, as the shock so got might be dangerous, if not fatal.

289. *Large Coil.*—The Induction Coil has been used very largely of late, in order to obtain information regarding the various forms of disruptive discharge. For this purpose several very large coils have been employed, the largest by far being that lately constructed by Mr Spottiswoode, represented in fig. 180.

The length of this enormous coil is 4 feet, its diameter 20 inches, and its total weight 15 cwt. It is supported at the ends by two massive pillars, and has also a support at the middle to prevent bending.

There are two primary coils, either of which can be inserted into the secondary—the one for producing long sparks, and the other for producing short dense sparks. In the former, which contains an iron core consisting of a bundle of rods, the circuit wire is 660 yards long, ·096 inch in diameter, and is wound on in six layers. The resistance is 2·3 ohms. In the latter, the iron core is thicker and the wire is wound double to diminish the resistance.

The length of wire on the secondary coil is 280 miles, its diameter ·0095 inch, and the total number of windings 341,850. For better insulation the secondary wire is wound

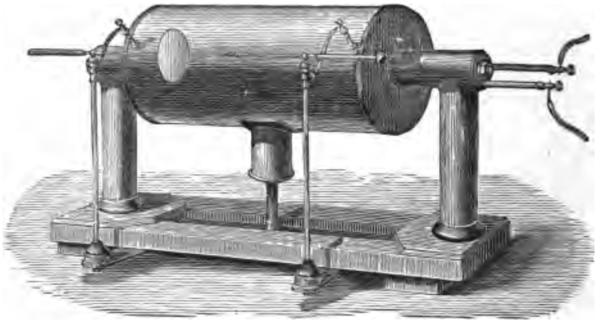


Fig. 180.

in sections separated by discs of vulcanite. The condenser consists of 126 sheets of tinfoil, 18 × 18·25 inches, separated by varnished paper.

The length of spark got from this coil is very great. With 5 quart Grove cells, the length of spark is 28 inches; with 10 cells, 35 inches; and with 30 cells, $42\frac{1}{2}$ inches. This last is by far the longest spark that has ever been produced by artificial means.

290. *Disruptive Discharge, Dielectric Strength.*—When two electrodes separated by a dielectric are charged to different potentials, the dielectric is, according to Faraday's theory, thrown into a particular state of stress, which is accurately represented by a tension along the lines of force between the electrodes, and an equal pressure in all directions at right angles to these lines. If the dielectric be air, and if p denote this tension, or pressure, we have for the value of p the equation

$$p = 2\pi\sigma^2; \qquad (1)$$

where σ denotes the quantity of electricity per unit of area on the surface of the electrode. Also if R denote the

resultant electric force at a point just outside the conductor, we have (sect. 155)

$$R = 4\pi\sigma. \tag{2}$$

By combining (1) and (2) we have

$$p = \frac{R^2}{8\pi}. \tag{3}$$

If the dielectric be any other medium whose specific inductive capacity is K, we have, of course, for p the value

$$p = \frac{KR^2}{8\pi}. \tag{4}$$

It is to be observed that p is a force exactly the same in kind as the tension which exists in a cord stretched between two points; and it can be expressed as so many pounds or grammes weight per unit of area. Hence we can speak of the *electric* tension of the dielectric, if we understand by that term the quantities represented in equations (3) and (4).

When the difference of potential between the electrodes is gradually increased, the value of p—the electric tension—also gradually increases, until a certain limit is reached, when the dielectric gives way under the strain put upon it, and a disruptive discharge, in the form of a spark, takes place between the electrodes. This limiting tension is called the *dielectric strength* of the medium.

If the electrodes consist of two parallel circular plates whose diameter is great in comparison to the distance between them, the above expression for p can be put into a slightly different form. For this case R is constant for every point of the space between the electrodes, unless very near the edges, and (sect. 155) has the value $\frac{V}{t}$, where V is the difference of potential, and t the distance between the electrodes. Hence, if V be the difference of potential, and t the distance between the electrodes when discharge just takes place, the dielectric strength is, for air,

$$p = \frac{V^2}{8\pi t^2}. \tag{5}$$

Now if we assume air to be a homogeneous dielectric whose dielectric strength, for given circumstances as to

pressure, dryness, &c. is constant, this equation (5) shews at once that the spark length, t, is directly proportional to the difference of potential, V. Sir William Thomson, however, has shewn experimentally that this is not the case. He used as electrodes two circular horizontal plates facing each other. The upper plate was made perfectly flat, but the lower one slightly convex upwards like a watch-glass, in order to make the spark always take the same path from centre to centre of the two discs. The difference of potential was measured by the absolute electrometer (sect. 167), and the distance between the plates by a fine micrometer screw. By using equation (5) the dielectric strength, for different thicknesses of the layer of air, was calculated and expressed in C. G. S. units. The result shewed that the dielectric strength was greater for a thin layer of air than for a thick one, or, to put it otherwise, the electro-motive force per inch of air required to produce a spark was greater for thin than for thick layers of air. Regarding this, Sir William Thomson remarks that it is difficult even to conjecture an explanation.

By using two balls connected with the opposite coatings of a condenser whose charge was measured by a Lane's jar, Snow Harris found that the length of spark in air and other gases was proportional to the electro-motive force. Later experiments, other than those of Sir William Thomson, have shewn that this law is not strictly accurate for all distances, and that several collateral circumstances, such as the form and size of the electrodes, the sign of the electricity, &c., exert an important influence upon the relation between spark-length and potential-difference.

Faraday experimented upon the dielectric strength of different gases, but was unable to find any simple law connecting it with any other physical quantity. He gives, however, the following order for the dielectric strength of some of the gases: Hydrogen, oxygen, carbonic acid, air nitrogen—hydrogen having the least. This order has been verified by the experiments of Wiedemann.

It seemed natural to suppose that some relation existed between the dielectric strength and pressure of air or other gaseous medium, and accordingly the discovery of this

relation has been made the object of several experimental inquiries. Snow Harris, experimenting with the apparatus already alluded to, found that the length of spark was inversely proportional to the pressure of the air or other gas through which it passed. By recent experiments, this law has been found to be approximately true, but only between the limits of pressure represented by eleven inches of mercury and the ordinary atmospheric pressure.

Mr Gordon has quite recently examined the subject by means of a large induction coil giving a seventeen-inch spark. Taking the spark between a point and a ball, he finds that the electro-motive force per inch of air required to produce a spark is greater for small than for large pressures —a result confirmatory of that of Sir William Thomson.

When the pressure of the gaseous dielectric is gradually increased above the atmospheric pressure, the dielectric strength also increases until a certain limit is reached, when it appears to become infinite. This has been shewn by M. Cailletet, who found that he could not, by a powerful induction coil, send a spark through half a millimetre of air at a pressure of between forty and fifty atmospheres.

Also, when the pressure is diminished, the dielectric strength gradually decreases, but not indefinitely so. It appears to reach a minimum value; and when the vacuum is very perfect, the spark from a powerful source can hardly pass over even a very short distance. In some vacuum tubes constructed by Hittorf and Geissler, a spark which passed readily through fifteen or twenty centimetres of ordinary air, could hardly pass through half a millimetre of the rarefied space. This may be due, however, in great part to a counter electro-motive force set up at the surface of separation between the electrode and the residual gas.

291. *Electric Egg.*—When the induced current is made to pass through nearly vacuous spaces, a very splendid effect is produced. The *electric egg* (fig. 181) is employed to display this. It consists of a glass vessel in the shape of an egg, with an open neck above, and another below. Brass fittings are attached to these. The lower opening is fitted with a stopcock, and can be screwed to the plate

of an air-pump. A brass rod and ball rise a short way into the egg. The fittings above are intended to allow of a rod ending in a ball passing up and down air-tight, so that the two balls can be conveniently set at different distances.

Fig. 181.

When the egg is exhausted, and the wires from the coil are attached, the one above and the other below, a luminous glow extends between the balls, which is wide in the middle, and contracts at either extremity. When the exhaustion has reached one-twelfth of an inch, as shewn by the gauge of the air-pump, black bands are seen to lie horizontally in the light, so as to wear the appearance of stratification, as shewn in the figure. These occur more readily when a drop or two of turpentine, alcohol, or ether have been introduced into the egg. The cause of the stratification is as yet a matter of speculation. The ball which forms the — pole is enveloped in a covering of blue light. The glow, which is of a beautiful mauve tint, appears to proceed from the + ball, and reaches nearly to the — ball, from which it is separated by a well-marked non-luminous space. By means of the commutator, these appearances at the balls can be instantly transposed.

292. *Vacuum Tubes.*—In order to examine the electrical discharge in various gases at different pressures, so-called vacuum tubes are usually employed. They are constructed by hermetically sealing the ends of a glass tube round two pieces of platinum or aluminium wire, which serve as electrodes. The tube is exhausted through a short piece of capillary tube attached to its side, and put in connection with the air-pump. The exhaustion is usually begun and carried as far as possible by an ordinary air-pump, and then finished by means of the Sprengel mercury pump—a form of pump which has been recently so much improved by Crookes, that an

exhaustion represented by a small fraction of a millimetre of mercury can be easily obtained. When the exhaustion has been carried as far as required, the capillary tube is melted in the blow-pipe flame and closed—a process in which the operator is helped by the pressure of the external air. When tubes containing different residual gases are required, they are first filled with the respective gases and then exhausted, leaving a trace of the gas. When different gaseous pressures in a closed tube are required, the following convenient method is adopted. A small glass bulb containing a piece of potass is attached, by a narrow tubular neck, to a point near the end of the main tube, but clear of its electrode. The potass has the property of absorbing, when cold, the residual gas, especially when carbonic acid gas is used, and of giving it out again when heated. To increase the pressure, the potass bulb is gently heated by a spirit-lamp flame so as to expel the absorbed gas; and, to diminish the pressure, the bulb is allowed to cool, or cooled artificially, so as to re-absorb more and more of the residual gas.

When the discharge from the Holtz machine or an induction coil is passed through air at different pressures, the following series of phenomena is observed.

At the ordinary atmospheric pressure the discharge takes the form of the *spark*, the *brush*, the *glow*, or the *band* discharge according to the electro-motive force of the machine and the distance between the electrodes.

When the pressure is reduced to about $\frac{1}{25}$th of an atmosphere, the discharge appears as a fine flexible streak of light extending the whole length of the tube, from one electrode to the other. The light is observed to have a reddish tint, which is due to the nitrogen present in the air.

When the pressure is reduced to $\frac{1}{40}$th of an atmosphere, a luminous haze is seen proceeding from the positive electrode, and filling the whole of the tube, with the exception of a short dark space in the neighbourhood of the negative electrode, but separated from it by a patch of light of a deep blue colour. An examination of this blue light by the spectroscope, shews that an increase of temperature has taken place at the negative electrode.

When the exhaustion is carried to $\frac{1}{150}$th of an atmosphere, the luminosity proceeding from the positive electrode is seen to be crossed by narrow dark spaces forming what are called

Fig. 182.

striæ, while the dark space near the negative electrode shews considerable increase, but is still separated from the electrode by a patch of light.

When the pressure is still further reduced, the striæ become more and more separated, forming detached blocks of light, with distinct dark spaces between them. The dark space near the negative electrode is also still further increased; and, as the exhaustion proceeds, a second dark space begins to shew itself quite close to the negative electrode, but separated from the first dark space by a solitary luminosity. This second dark space has been recently carefully studied by Crookes, and, after him, has received the name of Crookes' space.

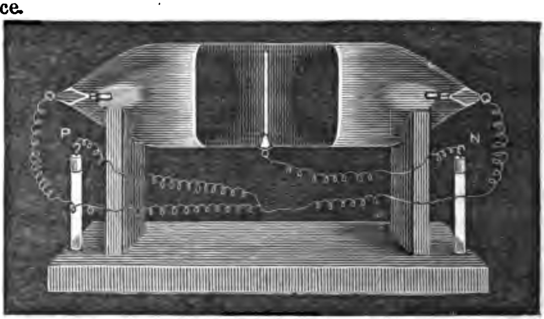


Fig. 183.

When the exhaustion is carried still further, and made as complete as possible, the striæ are seen gradually to disappear as if they fell one by one into the positive electrode, until,

eventually, the Crookes' space has so much increased as to fill the whole length of the tube. In this condition the exhaustion is so perfect, and the number of molecules of residual gas, comparatively speaking, so small, that the molecules are able to proceed in parallel streams from the negative to the positive electrode without coming into collision with one another. In the language of the kinetic theory of gases, the length of the mean free path of the molecules is now equal to the length of the tube. In this high vacuum, the stream of molecules proceeding from the negative electrode is observed to go in parallel lines, and to produce a beautiful phosphorescent light where it strikes against the surface of the glass. The colour of this light varies with the kind of glass, but is independent of the nature of the residual gas. With uranium glass, the phosphorescence is a dark green; with English glass, blue; and with soft German glass, a bright apple-green. When the molecular stream is directed against a diamond inclosed in a tube, the diamond phosphoresces with a bright green colour, giving almost as much light as a candle. When the stream falls on a cluster of rubies, each ruby glows with a brilliant red glow.

By using wide tubes of suitable shape, Mr Crookes has shewn that the shadow of any object placed in the path of the molecules is thrown upon the end of the tube; and he has also exhibited the curious experiment of making the molecular stream drive a delicately balanced wheel, with mica vanes, supported on pivots inside the tube.

The character of the discharge in a vacuum tube is found to depend greatly upon the size of the negative terminal. When this is small, the tube appears to expose a resistance to the passage of the discharge, and the striation is formed with greater difficulty. This is shewn by having a tube with one large and one small terminal, and sending the discharge through it alternately in opposite directions. When the small terminal is negative, the striæ are very faint, if at all present; but when the large terminal is negative, they come out with great distinctness.

Goldstein has recently shewn that the negative terminal,

though not the positive, can be replaced by a thin sheet or cylinder of non-conducting material, provided it be perforated by a number of small holes. With this form of negative, striation and all the other phenomena of vacuum tubes come out almost as well as with a metallic electrode.

When a magnet is presented to a vacuum tube through which a discharge is passing, the discharge is seen to be deflected, one pole appearing to attract and the other to repel it. This is obviously analogous to the known action of a magnet upon a movable conductor carrying a current. And not only does the magnet act upon the discharge as a whole, but, when closely examined, it is also found to have a similar action upon each individual stria, giving one the impression that each stria is a complete separate discharge.

Another remarkable phenomenon connected with the discharge in vacuum tubes remains to be noticed—the phenomenon, namely, of the *sensitive state*. This is the name given to the state of the discharge when it is affected, in the way of being either attracted or repelled by the approach of a conductor, such as the tip of the finger, to the side of the tube.

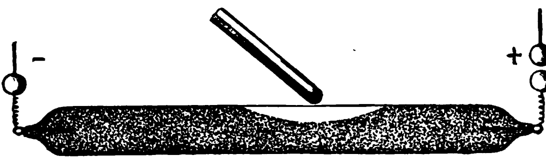


Fig. 184.

In all cases the sensitive state is found to be due to the discharge being intermittent, and this intermittence is most easily produced by interposing an air-space between the terminal of the machine and the terminal of the tube. This is called including an *air-spark* in the circuit. When the air-spark is positive—that is, when the gap is between the terminal of the tube and the positive terminal of the machine—the approach of the conductor causes a repulsion of the discharge; and, when the air-spark is negative, an attraction is produced. The explanation usually given of this phenomenon

is as follows: On account of the intermittent nature of the discharge, a greater quantity of electricity is sent through the tube at each discharge than if the discharge were more continuous. This quantity of electricity produces a charge on the inside surface of the glass of the tube, and perhaps also in the particles of the gas themselves. Hence, when a conductor connected to earth is brought near to the tube, it is acted upon inductively by the charge on the tube, and a redistribution of the electricity takes place at the point opposite the end of the conductor. In this way the conductor comes to act as a second terminal. Now, when the air-spark is positive, the induced electricity on the end of the conductor will be negative, and, in consequence, it will act as a second negative terminal, and produce the usual appearance of a dark space which accompanies the negative electrode. Hence the charge will seem to be repelled. On the other hand, when the air-spark is negative, the point of the conductor will be positively electrified by induction through the tube, and will act as a positive terminal, producing the usual luminosity and striation which proceed from the positive electrode. Hence, in this case, the discharge will appear to be attracted. The above explanation is not, in all points, quite satisfactory, and more experimenting is needed to bring out the full explanation of the phenomenon. This subject, along with the whole phenomena of vacuum tubes, has been recently studied with great care by Mr Spottiswood, whose results are to be found in the *Philosophical Transactions*.

MAGNETO-ELECTRIC INDUCTION—MAGNETO-ELECTRICITY.

293. *Magneto-electricity* includes all phenomena where magnetism gives rise to electricity. There are practically two cases of it—namely, when the current is induced in a coil of insulated wire, and when it is induced in conducting-plates.

Currents induced by Magnets in Coils of Wire.

294. *How a Current is induced in a Coil by a Magnet.*—When a coil, in which a current circulates, is quickly placed

within another coil unconnected with it, a contrary induced current in the outer coil marks its entrance, and when it is withdrawn, a direct induced current attends its withdrawal. Change, whether in the position or current strength of the primary coil, induces currents in the secondary coil, and the intensity of the induced current is in proportion to the amount and suddenness of the change. In singular confirmation of Ampère's theory, a permanent bar-magnet may be substituted for the primary coil in these experiments, and the same results obtained with greater intensity. When a bar-magnet is introduced into the secondary coil, a current is indicated; and when it is withdrawn, a current in a contrary direction is observed; and these currents take place in the directions required by Ampère's theory. A change of position of the magnet is marked by a current, as in the former case. If we had the means of increasing or lessening the magnetism of the bar, currents would be induced the same as those obtained by strengthening or weakening the current in the primary coil. It is this inductive power of iron at the moment that a change takes place in its magnetism, that forms the basis of magneto-electric machines. The manner in which this is taken advantage of will be easily understood by reference to fig. 185. NS is a permanent horseshoe magnet, and let us suppose it to be fixed; CD is a bar of soft iron, with coils A and B wound round its extremities, and may be looked upon as the armature of the magnet. CD is capable of rotation round the axis EF. So long as CD remains in the position indicated in the figure, no currents are induced in the surrounding coils, for no change takes place in the magnetism induced in it by the action of NS. The moment that the poles

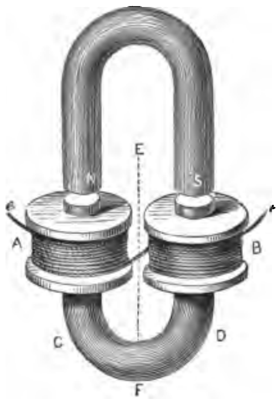


Fig. 185.

of CD leave NS, the magnetism of the soft iron diminishes as its distance from NS increases, and when it stands at right angles to its former position, the magnetism has disappeared. During the first quarter-revolution, therefore, the magnetism of the soft iron diminishes, and this is attended in the coil (for both coils act, in fact, as one) by an electric current, which becomes manifest when the ends, *e*, *e*, of the coil are joined by a conductor. During the second quarter-revolution, the magnetism of the armature increases till it reaches a maximum, when its poles are in a line with those of NS. A current also marks this increase, and proceeds in the same direction as before; for though the magnetism increases instead of diminishes, which of itself would reverse the induced current, the poles of the revolving armature, in consequence of their change of position with the poles of the permanent magnet, have also been reversed, and this double reversal leaves the current to move as before. For the second half-revolution, the current also proceeds in one direction, but in the opposite way, corresponding to the reversed position of the armature. Thus, *in one revolution of a soft iron armature in front of the poles of a permanent magnet, two currents are induced in the coils encircling it, in opposite directions, each lasting half a revolution, starting from the line joining the poles.*

Currents induced by Magnets in Conducting-plates.

295. The *Magnetism of Rotation* was discovered by Arago in the years 1824–5. He observed that when a magnetic needle was made to oscillate immediately above a copper plate, it came sooner to rest than it did otherwise. The oscillations were made in the same time as when away from the plate, but they were less in extent: the plate seemed thus to act as a damper to the motions of the needle. This being the action of the plate at rest on the needle in motion, Arago reasoned that the needle at rest would be influenced by the plate in motion. Experiment confirmed this surmise. He made a copper disc revolve with great rapidity under a needle, resting on a membrane placed right over the disc, and quite unconnected with it, the middle of the needle being

placed above the centre of the disc. As expected, the needle deflected in the direction of the motion of the disc. The deflection of the needle increased with the rapidity of the motion, and when it reached a sufficient amount, the needle no longer remained in a fixed position, but turned round after the disc. This action of the revolving disc was attributed to what was then called the 'Magnetism of Rotation,' and the name has been since retained. The explanation of this phenomenon was first given by Faraday (1831). He proved it to arise from the reaction of currents induced in the plate in motion by the magnet.

296. The magnetism of rotation is only one of a very large class of phenomena, in which the motion either of a magnet or a wire conveying a current induces a current in a neighbouring conductor.

With the aid of Lenz's law, we can easily understand the principles at work in Arago's revolving plate. Fig. 186 represents what takes place in it. The plate, P P, may be regarded as divided into four parts; those of which *n*, *n'*, *s*, *s'* form the centres. The part *n* approaches the north pole, N, of the magnetic needle NS. In order to impede the motion of approach, *n* must be forced to assume north polar magnetism, the current of which moves, as shewn in the figure, from right to left. The part of which *n'* is the centre, leaving a south pole, will be induced to assume north polar magnetism to impede the rotation of the disc. The currents of *n* and *n'* are coincident at their further ends, but in the middle, as shewn by the dotted lines, they are opposed, the result of which is that one current circulates, as shewn by the continuous line in the left-hand side of the plate. A similar state of things is also found in the right-hand half, as shewn in the figure. The two main currents are coincident in the middle of the plate. It is this conjoined current which

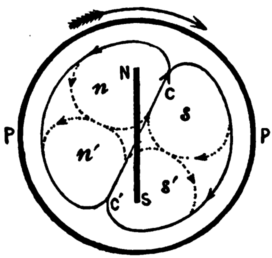


Fig. 186.

affects the needle; it runs in a direction a little in advance of the needle, as the inductive power of the magnet takes some time to act. As the induced current lies below the needle, the deflection, according to the rule, takes place in the direction of the motion of the disc. If the disc were stationary, the currents induced in the plates would manifestly impede the oscillations of the needle. When cuts are made in the disc in the line of the radii, it loses almost entirely its disturbing power; the currents formed in the whole disc can no longer take place, and those formed in the various sectors are weak in comparison; by filling up the vacant spaces with solder, the power is nearly restored to it. As is to be expected, the effect of the revolving plate depends on the conducting power of the material of which it is made. It is owing to its high conducting power that copper is so much used in these experiments; hence, also, it is that copper is so much employed in the construction of magnetic apparatus. A copper compass-box, for instance, is not only desirable, from its being free from iron, but it acts also as a damper to bring the needle quickly to rest when disturbed.


Fig. 187.

297. Lenz's law is applicable to all cases when electricity is induced by the motion of a magnet, or of a conducting circuit. We may quote only two other experiments as illustrations of it. In the first experiment, a small cube of copper (fig. 187) is hung by a thread to a frame, and placed between the poles of a powerful electro-magnet; the cube is sent into rapid rotation by the twist on the thread, previously given it; it is instantly brought to a halt, when the current is allowed to circulate in the coils of the magnet, and it begins its motion again when the current is turned off. In the second experiment, a disc of copper (fig. 188) is made to rotate rapidly between the poles *n*, *s*, of an electro-magnet, by means of a handle and intervening wheelwork turned by the experimenter. When the current

magnetises the soft iron poles, the disc, moving freely before, appears suddenly to meet with an unseen resistance, and the rotation continues slowly or not at all. If persisted in, the rotation causes the disc to rise in temperature, *the rise being proportionate*, according to Foucault, *to the square of the velocity of rotation*. As shewn in the figure, the approaching part of the disc has a south pole turned to *s* and a north pole to *n*. The receding part manifests the opposite polarity, both polarities combining to resist the motion of the disc. The currents marked with dotted lines are not the only currents. There are several such currents in the same direction, extending out like waves on each half, coinciding in the line between the centre and the poles. Hence, if a circuit were formed, including the radius between the centre and the two poles, a current in one direction would be constantly transmitted through it. This may be done by connecting a wire with the axis of the plate, and by making a spring press on the edge of the plate, at the poles, so as to give a path for the current without impeding the plate. To the spring a wire must also be attached. The two wires being connected with a galvanometer, a current in one direction would be indicated by it as the plate revolves. A machine of this kind, invented by Faraday (1831), was the first form of the magneto-electric machine, Chapter XXII.

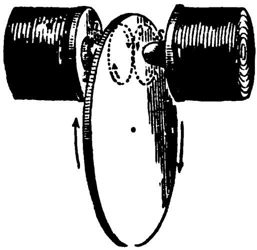


Fig. 188.

ABSOLUTE ELECTRICAL MEASUREMENTS.

298. *How an Electric Resistance may be expressed as an Absolute Velocity.*—It has already been shewn (sect. 186) that the dimensions of a resistance are the same as those of a velocity; and it becomes an important experimental problem to find the velocity which is equivalent to the resistance of a wire of given length, thickness, and material. This has been done by the British Association Committee, in order to find

in absolute measure the value of the *ohm* or B.A. unit, as it is called. The method adopted will be understood from what follows: Suppose, at any part of the earth's surface, two rails are placed parallel to each other, so that the plane passing through them shall be perpendicular to the magnetic meridian, or to the lines of horizontal force. We may thus put the rails horizontally, the one lying right above the other. Suppose now that a rod, standing vertically, connects these rails, and can be slid along without friction between them. Let the ends of the rails at either termination be connected with a rod of equal length to the slider, and let it be placed in the magnetic meridian, or at right angles to the plane in which the slider moves. Let this rod be bent so as to form an arc of 57¼° of a circle, the radius of which must be the length of the rod or of the slider, and let a small needle be suspended at the centre. There will be thus a complete conducting circuit formed by one rail, the rod, the other rail, and the slider. Let the resistance, moreover, throughout this circuit be the same, whatever the position of the slider in the rails, or, which is the same thing, let the rails be perfect conductors. When the sliding rod is moved, it cuts the horizontal lines of magnetic force at right angles, and a current is induced by them in it, the strength of which is proportionate to the number of lines cut by it in a given time. The faster, therefore, the rod moves, the greater is the current, and the greater will be the deflection of the small needle. When it is moved with such a velocity that the needle deflects 45°, the current in the arc has acquired the same power over the needle as the earth's magnetism. The current induced in the slider is in such a direction that the vertical action between it and the earth's magnetism offers resistance to its further motion, and work therefore has to be expended to move the slider. The work expended in a given time, say a second, in moving the rod, is within the circuit equivalent to the electro-motive force, or the work done in producing the current. If the resistance within the circuit which the electro-motive force has to overcome in generating a current capable of causing a deflection, say of 45°, be small, the velocity of the slider will be correspondingly small; if

great, correspondingly great. The velocity of the slider thus measures the resistance of the circuit.

Although this arrangement, which contains the germ of the reasoning, cannot be practically carried out, other arrangements can by calculation be reduced to it. To fix our ideas, let the slider be a metre in length; let it move, say, 10,000 metres per second to cause a deflection of 45°—that is, to generate a unit current in the supposed circuit. The slider, in moving at this rate, describes an area of 10,000 square metres, which is the measure of the number of lines of force cut, or of the inductive power of the earth's horizontal magnetism in the experiment. It may be obtained, as in this case, by a slider of a metre in length moving at the rate of 10,000 metres per second, or one 100 metres in length moving with $\frac{1}{100}$th part of the velocity—that is, 100 metres.

Suppose, now, I wish to know the resistance offered by a wire of a certain thickness, expressed as a velocity, I bend 6·2832 metres of it into the form of a ring of one metre in radius, and make the ring capable of rotation round a vertical, as it is in fig. 188, round a horizontal axis. The induction to which the ring is subjected in its rotation, causes two opposite currents to traverse it in one revolution, the turning-point being when the ring is at right angles to the magnetic meridian; but since each half changes its side with each change of current, to an observer north or south of the ring the current appears to move always in the same direction, and it consequently affects a needle placed at its centre in the same way. To reduce the motion of the ring to the equivalent motion of the slider, we must project the motion of the ring on a vertical plane at right angles to the magnetic meridian. The semi-revolution of the sphere described by the ring projected on this plane is the area included by the ring, namely, 3·1416 square metres, and by a whole revolution twice this, or 6·2832 square metres. If ten revolutions per second produce a deflection of 45°, the effective area is 62·832, which is equivalent to a metre slider moving at the rate of 62·838 metres per second. But we reckon the current from one metre of it, so that the velocity of the ring must be 6·2838 times increased to give one metre

the effect of the whole circumference : the equivalent velocity of the metre slider must thus be 394·7. The resistance of 6·2832 metres of the wire in question is thus 394·7 metres per second, and we can easily calculate the length of it necessary to produce a resistance of one metre, or of 10,000,000 metres, the B.A. unit. Here we have only given the mere outline of the process of estimating resistance as an absolute velocity. It was essentially by this method, which is due to Sir William Thomson, that Messrs Maxwell, Stewart, and Jenkin (1863–4), with almost perfect experimental and mathematical skill, measured the absolute resistance of a coil instead of a ring of copper wire, and thence obtained a material value for a B.A. unit. Should the material standard they found be lost or damaged, it could be again renewed by a new determination.

299. *Relation between the Electro-static and the Electro-magnetic Systems of Units.*—These systems have already been explained (sects. 183, 185), and it has been shewn (sect. 186) that the ratio of the electro-static to the electro-magnetic unit of quantity of electricity, is a quantity whose dimensions are the same as those of a velocity. Denoting this ratio by v, we can obtain by means of it a set of equations connecting the numbers which express in electro-static and electro-magnetic measure the same quantity of electricity, the same current, the same electro-motive force, the same resistance, and the same capacity.

(1) Let q and Q be the electro-static and the electro-magnetic measure of the same quantity of electricity. Then evidently we have

$$q = v\mathrm{Q}. \tag{1}$$

(2) Let c and C be the electro-static and the electro-magnetic measure of the same current; and let q and Q be the electro-static and the electro-magnetic measure of the quantity of electricity conveyed by the current in the time t; then we have

$$q = ct,$$

and $$Q = \mathrm{C}t;$$

but $$q = vQ \qquad \text{by (1).}$$

Therefore $$ct = vCt;$$
therefore $$c = vC. \qquad (2)$$

(3) Let e and E be the electro-static and the electro-magnetic measure of the same electro-motive force, and let q and Q be the electro-static and electro-magnetic measure of the quantity of electricity transferred from one point to another whose difference of potential is e or E; then the work done is represented by qe or QE. Hence,

$$qe = QE;$$
but $$q = vQ.$$
Therefore $$vQe = QE.$$
Hence $$e = \frac{E}{v}. \qquad (3)$$

(4) Let r and R be the electro-static and the electro-magnetic measure of the resistance of the same wire; and let e and E be the electro-static and electro-magnetic measure of the difference of potential between its ends, and c and C the electro-static and electro-magnetic measure of the current through it; then, by Ohm's law, we have

$$c = \frac{e}{r},$$
and $$C = \frac{E}{R}.$$
Therefore $$\frac{c}{C} = \frac{e}{r} \cdot \frac{R}{E};$$
but $$c = vC,$$
and $$e = \frac{E}{v}\ (3).$$
Therefore $$\frac{vC}{C} = \frac{E}{v} \cdot \frac{1}{r} \cdot \frac{R}{E}.$$
Hence $$v = \frac{R}{vr}, \text{ that is, } r = \frac{R}{v^2}. \qquad (4)$$

(5) Let s and S be the electro-static and the electro-magnetic measure of the capacity of the same condenser; and let q and

Q be the electro-static and electro-magnetic measure of the charge in it, and e and E the corresponding measures of the difference of potential; then

$$q = es,$$

and $$Q = ES;$$

but $$q = vQ,$$

and $$e = \frac{E}{v}.$$

Therefore $$vQ = \frac{E}{v}.s.$$

Hence $$v.ES = \frac{E}{v}.s;$$

therefore $$s = v^2S. \quad (5)$$

The above equations indicate five distinct methods of finding the value of v.

Weber and Kohlrausch compared the two measures of the same quantity of electricity, that quantity being the charge of a Leyden jar. The difference of potential between the coatings was obtained directly by an electrometer. The capacity was expressed in absolute measure by finding the radius of a sphere which had the same capacity as the jar. The product of these two numbers gave the quantity of electricity in the jar in electro-static measure. The jar was then discharged through the coil of a galvanometer, and, from the swing of the needle, the number representing the electro-magnetic measure of the charge was obtained. The ratio of the two numbers gave the value of v, which was

$$v = 3{\cdot}1704 \times 10^{10} \text{ centimetres per second.}$$

Sir William Thomson compared the two measures of the same electro-motive force. The electro-motive force in electro-static measure was obtained directly by an electrometer. The electro-magnetic measure was obtained by observing the current which it could send through a wire of known resistance, and applying Ohm's law. The ratio of the two numbers gave for v the value

$$v = 2{\cdot}93 \times 10^{10} \text{ centimetres per second.}$$

Clerk Maxwell also compared the two measures of the same electro-motive force, but by a different method. He balanced the electro-static repulsion of two similarly charged insulated discs against the electro-magnetic attraction of two flat spiral coils of known resistance and carrying known currents. This method gave for v the value

$$v = 2{\cdot}8798 \times 10^{10} \text{ centimetres per second.}$$

The other methods indicated by the above equation have also been employed by different experimenters, and results obtained fairly concordant with the values already given.

300. *Physical meaning of v.*—An idea of the physical meaning of v may be got as follows. We may evidently regard an electric current as a close succession of statically charged bodies, each containing the quantity of electricity which the current transmits in a second, and all moving with the velocity of electricity. Hence, if we have two bodies statically charged with like electricity, moving in the same direction, and with the same velocity in parallel lines, we see that, at a certain velocity, the electro-static repulsion between the bodies will just be balanced by the electro-magnetic attraction arising from the parallel currents produced by their motion. If V be this velocity, then it can be shewn that $V = v$. This result was predicted by Clerk Maxwell, and has been so far verified by Professor Rowland, who has shewn that an insulated statically-charged rotating disc has a distinct electro-magnetic action on a freely suspended astatic needle.

Part IV.—PRACTICAL APPLICATIONS OF CURRENT ELECTRICITY.

CHAPTER XXIII.

ELECTRO-METALLURGY.

301. *Electro-metallurgy* is the art of depositing, electro-chemically, a coating of metal on a surface prepared to receive it. It may be divided into two great divisions—electrotype and electro-plating, gilding, &c.—the former including all cases where the coating of metal has to be removed from the surface on which it is deposited, and the latter all cases where the coating remains permanently fixed. Gold, platinum, silver, copper, zinc, tin, lead, cobalt, nickel, can be deposited electrolytically.

302. *Electrotype* is the art of copying seals, medals, engraved plates, ornaments, &c., by means of the galvanic current in metal, more especially copper. The manner in which this is done will be best understood by taking a particular instance. Suppose we wish to copy a seal in copper: an impression of it is first taken in gutta-percha, sealing-wax, fusible metal, or other substance which takes, when heated, a sharp impression. While the impression—say, in gutta-percha—is still soft, we insert a wire into the side of it. As gutta-percha is not a conductor of electricity, it is necessary to make the side on which the impression is taken conducting; this is done by brushing it over with plumbago by a camel-hair brush. The wire is next attached to the zinc pole of a weakly charged Daniell's cell, and a copper plate is attached by a wire to the copper pole of the cell. When the impression and the copper plate are dipped into a strong solution of the sulphate of copper, they act as the − and + electrodes. The copper of the solution begins to deposit itself on the impression, first at the black-leaded surface in the vicinity of the connecting

wire, then it gradually creeps over the whole conducting surface. After a day or two, the impression is taken out; and the copper deposited on it, which has now formed a tolerably strong plate, can be easily removed by inserting the point of a knife between the impression and the edge of the plate. On the side of this plate, next the matrix, we have a perfect copy of the original seal. If a medal or coin is to be taken, we may proceed in the same way, or we may take the medal itself, and lay the copper on it. In the latter case, the first cast, so to speak, that we take of each face is negative, shewing depressions where the medal shews relief; but this is taken as the matrix for a second copy, which exactly resembles the original. The adhesion between the two is slight, and they can be easily separated. The cell of a battery is not needed to excite the current. A galvanic pair can be made out of the object to be coated and a piece of zinc. Fig. 189 shews how this may be done. B is a glass vessel, containing sulphate of copper; A is another, supported on B by a wire frame, and containing a weak solution of sulphuric acid. The glass vessel, A, is without a bottom, but is closed below by a bladder. A piece of zinc, Z, is put in the sulphuric acid, and a wire, D, coated with insulating varnish, establishes a connection between it and the impression, C, which is laid below the bladder. Electrotype is of the greatest importance in the arts: by means of it, engraved copper plates may be multiplied indefinitely, so that proof-impressions need be no rarity; wood-cuts can be converted into copper; bronzes can be copied; and several like applications are made of it too numerous to mention. By connecting a copper plate ready for corrosion with the + pole, and making it a + electrode, it can be etched with more certainty than with the simple acid, and without the acid fumes.

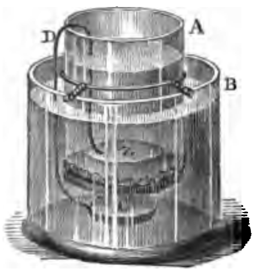


Fig. 189.

303. *Electro-plating.*—This is the art of coating the baser

metals with silver by the galvanic current. It is one theoretically of great simplicity, but requires in the successful application of it very considerable experience and skill. Articles that are electro-plated are generally made of brass, bronze, copper, or nickel silver. The best electro-plated goods are of nickel silver. When Britannia metal, iron, zinc, or lead are electro-plated, they must be first electro-coppered, as silver does not adhere to the bare surfaces of these metals. Great care is taken in cleaning the articles previous to electro-plating, for any surface impurity would spoil the success of the operation. They are first boiled in caustic potash, to remove any adhering grease; they are then immersed in dilute nitric acid, to dissolve any rust or oxide that may be formed on the surface; and they are lastly scoured with fine sand. Before being put into the silvering bath, they are washed with nitrate of mercury, which leaves a thin film of mercury on them, and this acts as a cement between the article and the silver. The bath where the electro-plating takes place is a large trough of earthenware or other non-conducting substance. It contains a weak solution of cyanide of silver in cyanide of potassium (water, 100 parts; cyanide of potassium, 10 parts; cyanide of silver, 1 part). A plate of silver forms the + electrode; and the articles to be plated, hung by pieces of wire to a metal rod lying across the trough, constitute the – electrode. When the plate is connected with the copper or + pole of a one or more celled galvanic battery, according to the strength required, and the rod is joined with the zinc or – pole, chemical decomposition immediately ensues in the bath, the silver of the cyanide begins to deposit itself on the suspended objects, and the cyanogen, liberated at the plate, dissolves it, re-forming the cyanide of silver. According, then, as the solution is weakened by the loss of the metal going to form the electro-coating, it is strengthened by the cyanide of silver formed at the plate. The thickness of the plate depends on the time of its immersion. The electric current thus acts as the carrier of the metal of the plate to the objects immersed. In this way, silver becomes perfectly plastic in our hands. We can by this means, without mechanical exertion or the craft of the workman,

convert a piece of silver of any shape, however irregular, into a uniform plate, which covers, but in no way defaces, objects of the most complicated and delicate forms. When the plated objects are taken from the bath, they appear dull and white; the dullness is first removed by a small circular brush of brass wire driven by a lathe, and the final polish is given by burnishing. The process of electro-gilding is almost identical with that of electro-plating, only the solution must be kept hot. Success in either is attained by proper attention to the strength of the battery, the strength of the solution, the temperature, and the size of the + electrode. Magneto-electric machines are now used very extensively for furnishing the necessary current in plating. For a description of these machines see Chapter XXIV.

ELECTRIC LIGHT.

304. When the ends of two wires which form the poles of a powerful galvanic battery are made to touch, and then are separated for a short distance, the current which passes when the contact is made does not cease with the separation, but forces its way through the intervening air, accompanied with an intense evolution of light and heat. So great is the heat evolved that the most refractory metals are melted by it, and therefore some substance rivalling the metals in conducting power, but much more infusible, must be found to act as the poles, to allow of the continuation of the current in such circumstances. The various forms of carbon are well suited to this purpose; the more compact forms of charcoal answer very well; baked carbon answers better; but the coke that is sublimed inside the retorts in the distillation of gas, both for durability and conducting power, makes by far the best poles. Sir Humphry Davy (1813) first discovered and described the electric light. Fig. 190 represents a simple arrangement for producing it. The carbon-points, P, N, are fixed into hollow brass rods, which are connected with the battery by wires entering at the binding screws *s*, *s*. The rods slide in the heads of the glass pillars A, A, fixed to a stand, so as to admit of the points being placed at different distances. The wires from the battery-poles being properly con-

nected, the points are made to touch, and are then withdrawn a line or two, when the most dazzling light ensues, rivalling the light of the sun in purity and splendour. Its intensity is such as to prevent the eye from examining the particulars of

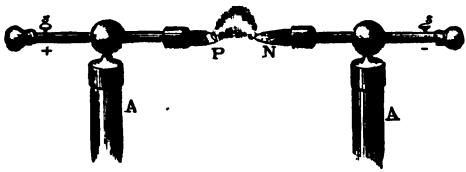


Fig. 190.

its production. These, however, may be ascertained by projecting with a lens of short focus the images of the points on a screen, when they are seen as shewn in the figure. The light is found to arise chiefly from the intense whiteness of the tips of the carbon rods, and partially from an arch of flame extending from the one to the other. This arch is called the *electric arc.* The + pole is the brightest and the hottest; a fact which may be proved by intercepting the current, when the + pole continues to appear red for some time after the − pole has become dark.

During the maintenance of the light, a visible change takes place in the condition of the poles. The + pole experiences a loss of matter; particles of carbon pass from it to the − pole, which they partly reach, and partly are burned by the oxygen of the air on the way. The same takes place, though to a much less extent, with the − pole; so that while the + pole becomes hollowed out or blunt by its losses, the − pole remains pointed by its apparent gains. The wasting away, particularly of the + pole, in a short time renders the distance between the poles too considerable to allow of the passage of the current, and the light is thus suddenly extinguished, until again renewed by contact and removal. The points may be removed with a powerful battery four or five millimetres before the circuit is broken. The transference of matter between the poles is considered to account for the existence of the arc, and

the passage through the air of the current, as thereby a conducting medium extends between the poles. The heat of this arch of flame, or *electric arc*, is the most intense that can be produced. Platinum melts in it like wax in the flame of a candle. Quartz, the sapphire, magnesia, lime, and other substances equally refractory, are forced by it into a state of fusion. The diamond, when placed in it, becomes white-hot, swells up, fuses, and is reduced to a black mass resembling coke. In this condition, it is still hard enough to scratch glass, but possesses almost no consistency, giving way to the pressure of the fingers.

The electric light is caused, not by the combustion of the carbon, but by its being brought into a state of incandescence. The electric light can, in consequence, be produced in a vacuum, and below the surface of water, oils, and other non-conducting liquids. It is thus quite independent of the action of the air, a circumstance which has been turned to useful account.

With a battery of some fifty Bunsen's elements, a light is produced of very great brilliancy; but when very great power is to be obtained, as well as brilliancy, twice or thrice that number must be employed. Fifty cells give a current sufficient to produce the light. If 150 cells be used, they are best arranged in three batteries, the + poles of all three being joined to form one + pole, and similarly with the − poles. With a battery of forty or fifty cells, no pointing of the rods is necessary, as this is done by the action of the electricity itself.

The spectrum of the electric light is found to abound in violet rays, and hence it is well adapted to photographic purposes. Fizeau and Foucault found that with a battery of 46 Bunsen cells, a light was obtained which had 34 times the photographic efficacy of the lime-ball light, both being tested by the effect produced on a plate covered with the iodide of silver. The same electric light, when compared in the same way with the sun, was found to stand as 23 to 100. For the production of the electric light, the various forms of dynamo-machines (Chap. XXIV.) are now all but universally employed.

305. *Electric Lamps.*—Various arrangements have been invented for maintaining the steadiness of the electric light. The aim in all such is to keep the carbon points, by some mechanical contrivance, within such a distance of each other that the current can pass between them. Foucault, aided by Duboscq, was the first (1849) who constructed an electric lamp of this description. In it, by aid partly of an electro-magnet, and partly of clock-work, the two points are made to travel towards each other at rates corresponding to those of their consumption, the + pole in this way travelling faster than the −. A detent is fixed to the keeper of the electro-magnet, which locks the clock-work when the keeper is brought up to the magnet, and withdraws it when it is away from it. The keeper is acted upon by a counter-spring, which draws it away from the magnet when the current does not circulate, or when it is too weak to act effectively. Thus, when the points waste away and separate from each other, the current becomes weaker, and when it gets so weak as to impair the splendour of the light, it is so arranged that the spring draws away the keeper, and thereby liberates the clock-work. The points are now made to approach until the current, by the nearing of the points, acquires sufficient strength to draw the keeper to it and insert the detent. There is thus a constant locking and unlocking of the clockwork, and the points are kept at the distance fitted to produce the most brilliant light.

The above is an example of one of the earliest forms of what are called focussing *arc lamps.* They are mostly used for experimental work in the laboratory; and not for general electric lighting, where it is not essential that the electric arc should always remain exactly at the same place. For the latter purpose, a great variety of non-focussing arc lamps has been devised. In them the upper carbon is allowed to approach the lower merely by the weight of the upper carbon-holder; and when the requisite distance for the arc to pass is reached, the upper carbon-holder is clamped by means of an electro-magnet actuated by the current itself. When the distance between the carbons becomes too great, the electro-magnet ceases, or partially ceases, to act, and the

weight of the carbon-holder again brings it down to the right distance. An early form of this lamp, made by Mr Hart, is represented in fig. 191. A is the upper carbon-holder, B the electro-magnet, and D the clamping arrangement worked by the armature F. When the current passes, A is drawn up by the magnet B, and the arc is produced. When the carbons waste, the magnet fails, and the points come together again, and the original process is repeated.

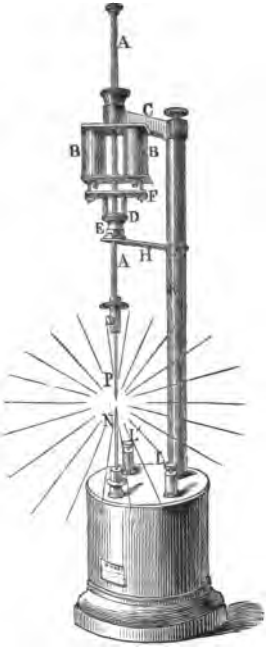


Fig. 191.

In Crompton's lamp, now much used, the upper carbon-holder in its descent turns a train of wheel-work, which can be instantly stopped by a friction break applied to the circumference of one of the wheels. The break is worked by an electro-magnet, and the clamping and unclamping take place with great regularity, and almost entirely avoid any blinking in the light.

An ingenious form of arc lamp was invented by Jablochkoff in 1876, and is known as Jablochkoff's candle. It is represented in fig. 192, where C and D are two thin carbon pencils separated by a thin layer of kaolin clay, B. The current, from an alternate-current machine, passes alternately up each carbon, and forms the electric arc at A; and in this way the two carbons are made to consume equally. Two or more of these candles are usually placed in one lamp, and an arrangement is provided whereby the current is automatically shifted from the one to the other as each in succession burns done.

Another form of arc lamp is represented in fig. 193, called the Wallace-Farmer lamp. A and B are carbon plates, the upper of which is controlled by the magnet C, by which

Fig. 192.

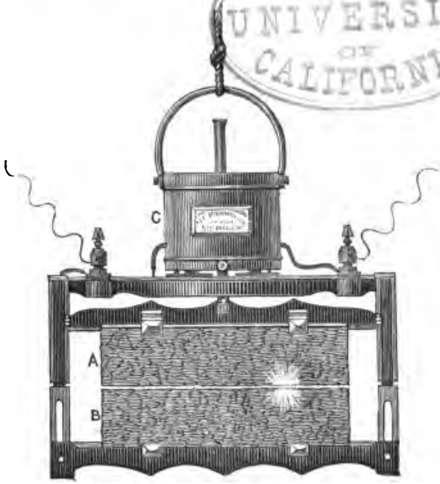


Fig. 193.

it is drawn up when the current passes, and the light springs out at the point where the requisite distance for the arc is found. When this part wastes, the light travels to another, and so on backwards and forwards along the carbons.

306. *Incandescent Lamps.*—When a strong current passes through a spiral of fine platinum wire, of the requisite resistance, the spiral is raised to a state of bright incandescence, and so becomes a source of light. This is the simplest example of an incandescent lamp, of which a considerable variety now exists. In Mr Swan's lamp the platinum spiral is replaced by a fine fibre of carbon prepared by carbonising a cotton thread at a high temperature, and in space void of air. The ends of the fibre are attached to

the electrodes, and the fibre is usually bent into a horse-shoe form, with a single spiral coil in the middle. The whole is inclosed in a small glass globe, which is exhausted very perfectly of air, and then hermetically sealed. The object of this is to prevent the rapid oxidation of the carbon when in a state of incandescence, which would soon make it consume away. Such a lamp will burn for 600 or 1000 hours without visible deterioration.

In Mr Edison's incandescent lamp, the carbon fibre is prepared by the carbonising process from a strip of bamboo cane. The other arrangements are similar to those of the Swan lamp. In order to prolong the life of the lamp, Mr Edison makes one end of his carbon fibre a little thicker than the other, and sends the current through the lamp always in the same direction.

Other examples of incandescent lamps in use are the Maxim and the Lane Fox, which, however, do not differ essentially from those described.

Incandescent lamps are found very serviceable for household illumination, seeing that a number of them, sometimes as many as forty, can be put upon one circuit, and lit by one machine.

307. The attempt which has been made to substitute the electric light for coal-gas in lighting up streets and public places, has proved very successful. By contrivances similar to those described above, the light may be continued for hours, and it has been used with excellent effect where a limited space has to be lit up, such as in the construction of bridges, at railway-stations, theatres, &c. It has also been applied with success to lighthouse illumination; and it has been found that the power of the electric light to penetrate fogs is immensely superior to that of the usual oil-light. At lighthouses the current is got from dynamo-machines, driven by steam-engines.

EXPLODING GUNPOWDER AT A DISTANCE.

308. The application of the galvanic current to exploding gunpowder at a distance depends on the power it has to ignite thin wires of comparatively bad conducting metals, such

as steel and platinum. The current must be transmitted to the point where the explosion is to take place by good conducting wires, and the thin wire is made to connect the two ends of these wires in the gunpowder. A red-heat is thus only developed at the spot where it is required. The circuit is not completed until all arrangements for the blasting are ready, and all persons connected with the preparations are at a safe distance from it. Roberts (1838) devised a method of conducting galvanic blasting which soon became almost universal. It is shewn in fig. 194. A tin tube, 3 inches long and ⅝ of an inch wide, is filled with gunpowder, and stopped with a cork at each end. Through one of the corks, two copper wires are inserted, ending in the cartridge in something like a pair of horns. The wires are insulated from each other by woollen yarn. They are continued without the cartridge for about 10 feet, when they part company so as to allow the battery wires to be attached to them. The ends of the horns within the cartridge are connected by a thin steel wire, ½ an inch in length, wound round and soldered to each of them. At the ends there is of course no insulating matter; indeed they must be filed or cleaned so as to make the connection with them and the thin wire complete. When a hole is bored for blasting, say 6 or 7 feet long and 2 inches wide, the charge of powder and the cartridge are inserted so that the cartridge lies in the middle of the charge, and the rest of the bore is filled with straw and sand in the usual way. The 10-foot wires project beyond the hole, and the battery-wires can be conveniently attached to them. When all is ready, the circuit is completed, and the explosion immediately follows. The steel wire is burnt away by the current, but the long copper wires are uninjured, and ready to be fitted up as before. Such cartridges are generally kept ready for use in mining establishments. In long circuits the function of the return wire may be performed by the earth, as in the electric telegraph.

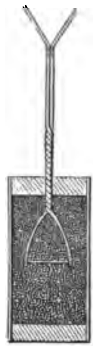


Fig. 194.

When several charges have to be fired at once, the whole

are generally included in one circuit. As there is always some difference in the steel wires, or in the way they are fitted, it not unfrequently happens that one cartridge is fired before the others. The circuit is thus broken, and the others are left unfired. With this arrangement, there is no certainty of a simultaneous discharge. If this is wanted, the galvanic current must be abandoned, and recourse must be had to the electricity of the induction coil. If the ends of the wires within the cartridge be brought so near that the induced current can leap over the distance between them, no steel wire is needed; the inductive spark itself can effect the ignition. After explosion, the distance of the ends remains the same, and the sparks continue. If, then, there be several charges to be fired in the same circuit, the firing of one does not stop the current, which continues even after all have been fired. The induction spark does not, however, kindle gunpowder with certainty, so that between the ends some material must be placed more easily ignited than gunpowder—such as white gunpowder, gun-cotton, &c. When the number of simultaneous explosions is great (five or six), some very readily exploded substance, such as fulminating mercury, must be placed in the path of the spark discharge.

Abel's fuses give us all that can be wished in the way of certainty and simplicity. Abel does not use a thin platinum wire between the two circuit terminations, but he uses what is in effect the same—a mixture that conducts, but conducts with difficulty. His fuses are primed with a mixture of chlorate of potassium, subphosphide of copper, and subsulphide of copper. The conducting ingredient is the subsulphide of copper, which must be added in such a proportion as to render the whole difficultly conducting. When the current passes through the mixture, it develops sufficient heat to explode it, and thereby the charge of gunpowder. Abel's fuses are chiefly intended for the electricity of the magneto-electric machine or of the induction coil, although the ingredients may be so compounded as to serve also for that of the voltaic battery. A very small machine is sufficient for the purpose. The little pocket machines employed for medical purposes fire readily one of these fuses.

They are very small, some of them about half an inch in length, and half the thickness of an ordinary pencil. From what has been said, the application of electricity to the firing of torpedoes under water can be readily understood.

ELECTRIC CLOCKS.

309. Electric clocks may be divided into two classes—those in which the impulse is given to the pendulum directly by electric power, and those in which it is given by a weight or spring alternately liberated and restrained by electricity. Of the first kind, that invented by Bain (1840) is best known. In the ordinary clock, it is the clock that moves the pendulum; in Bain's clock, it is the pendulum that moves the clock. As the construction of the pendulum is the only part of it connected with electricity, we shall confine our notice to a general description of the pendulum action. The lower part of the pendulum arrangement is shewn in fig. 195. The bob, B, consists of a bobbin of insulated copper wire, and is hollow in the centre; the wires *w*, *w* from both ends run along each side of the pendulum rod R (the lower part of which alone is seen), and are in metallic connection respectively with the two springs from which the pendulum hangs. Two magnets or bundles of magnetic rods, NS, N′S′, are fixed at either side of the bob, and are of

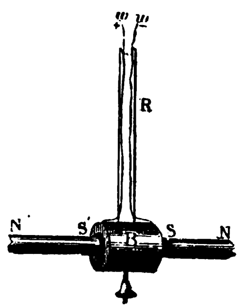


Fig. 195.

such dimensions that the hollow bob in its oscillation can pass a certain way over each without touching. The magnets have their like poles turned towards each other. The two springs of the pendulum rod are in connection with the two poles of a galvanic battery. In the connection between one of these springs and the battery, there is a break (not shewn in the fig.), worked by the pendulum rod. When the pendulum is made to move, say towards the right, it shifts a slider, so as to complete the connection between the poles of the

battery. The current thereupon descends one of the wires of the pendulum, passes through the coil of wire forming the bob, and ascends by the other. In so doing, it converts the bob into a temporary magnet, the south pole towards the right, and the north pole towards the left. In this way, the south pole of the bob is repelled by the south pole, S, of the right-hand magnet; and its north pole is attracted by the south pole, S′, of the left-hand magnet, so that from this double repulsion and attraction both acting in the same direction, the bob receives an impulse towards the left. Partly, therefore, from this impulse, and partly from its own weight, the pendulum describes its left oscillation; and when it reaches the end of it, it moves the slider so as to cut off the battery current, and then returns towards the right, under the action simply of its own weight. On reaching the extreme right, as before, it receives a fresh impulse; and thus, under the electric force exerted during its left oscillation, the motion of the pendulum is maintained. So long as the electricity is supplied, the pendulum will continue to move. The current required is exceedingly weak, and Bain considered that it could be sufficiently excited by a plate of copper and a plate of zinc sunk into the ground, and acted upon by the moisture usually found there. This *earth-battery*, as he called it, was expected to act steadily for years; but the result proved far otherwise, for the soil not unfrequently dried up, leaving no trace of electrical action. The imperfection of the battery has led to a strong prejudice against these clocks—stronger, certainly, than they merit. It has been found, however, by those who have employed them for astronomical purposes, that little dependence could be placed on them, and that the proper conditions of pendulum motion were, from the unsteady supply of electricity, interfered with; hence the opinion has been generally accepted, that a pendulum moved immediately by electricity, does not keep very accurate time; and the efforts that have of late been made in electric clock-making, have aimed at rendering the pendulum independent of the irregularities of the motive agent.

A very important application of Bain's pendulum has been

made by Mr Jones of Chester. Shortly after the invention of Bain's clock, Professor Wheatstone suggested that any number of such clocks could be made to move simultaneously by the same current of electricity. Mr Jones has turned this idea to account in the following way. A standard clock of the usual construction is made, by regulating the flow of a galvanic current, to control the action of any number of copying clocks, likewise of ordinary construction. The pendulum of the standard clock, itself in no way under electric control, on passing towards the right, touches a spring placed at the side, thereby completing the battery connection, and a current is transmitted to the copying clocks in a certain direction. On passing to the left side, the same takes place, but the current this time is sent through the circuit in the opposite direction. The pendulums of the copying-clocks are made on Bain's principle, but have, of course, no break to move, as the primary pendulum performs that function. Let us suppose, at first, that all the pendulums are at rest; in this case, no current is transmitted. Let the standard pendulum now be moved to the right, the right spring is touched, and a current at the same instant circulates through the bobs of the copying pendulums, and they thereby receive a simultaneous impulse towards the left. All the pendulums move then to the left; and on reaching the extremity of this oscillation, the standard pendulum touches the left spring, and the secondary pendulums are now impelled to the right. The motion of each secondary pendulum soon increases, until it reaches its proper extent. The pendulums once set a-going are, however, not intrusted solely to the stimulus of the electricity, but are moved by their own weights, as in ordinary clocks, so that if the electricity ceased to be sent to them, they would go on without it. It might be supposed that a confusion of the two forces, electricity and gravity, would ensue; such, however, is not the case. While the motion of the clock is intrusted to its own weight, the pendulum submits docilely to the controlling action of the electricity; and thus a copying clock of little value may be invested with all the perfection of the most costly observatory clock. The success of Jones's pendulum has been severely tested in the arrangement employed by

Professor Piazzi Smyth for firing the one o'clock time-gun at Edinburgh. A clock in the castle of Edinburgh is made to liberate the trigger of the gun exactly at one o'clock. This clock is regulated on Jones's principle, by a clock at the Observatory on the Calton Hill, nearly a mile distant. The Observatory clock, by means of electricity, sets off a time-ball on Nelson's Monument, about 100 yards off, at the same instant. The fall of the ball, and the flash of the gun, though occasioned each by its own clock, are perfectly simultaneous.

In the second class of electric clocks, the electricity is not charged immediately with the maintaining of the pendulum motion, but draws up the weight, or liberates the spring which discharges that function. This is the same principle as holds in what is known in horology as the 'remontoir' escapement. Mr Shepherd of London was the first to introduce this principle into electric clock-making, and one of his clocks on a large scale was exhibited at the Exhibition of 1851. We have now all over the country, clocks regulated to Greenwich time by means of electricity.

CHAPTER XXIV.

MACHINES FOR CONVERTING MECHANICAL WORK INTO ELECTRICITY, AND CONVERSELY.

310. Machines for converting mechanical work into electricity may be divided into two great classes—first, those for producing static electricity; and, secondly, those for producing dynamic or current electricity.

Of the first class we have two kinds—namely, those in which the electrification is produced by friction, and those whose action depends on the principle of electric induction. The most common example of the first class is the ordinary cylinder, or plate-glass electric machine, already described. Here we have a cylinder, or circular plate of glass of suitable thickness, made to revolve against a rubber of silk or amalgamated leather pressed against it by means of a spring. The

glass moves away from the rubber with a strong positive charge of electricity, while the rubber receives an equally strong negative one. As the glass moves round it meets, on the side opposite the rubber, a row of points attached to an insulated metallic ball, or cylinder with rounded ends, called the prime conductor. The positive charge on the glass acts, through the thin stratum of air, inductively on these points, and deposits a positive charge of electricity on the prime conductor, while a corresponding negative charge passes from the latter to the glass. If we suppose the action of the machine to be theoretically perfect, the glass will leave the row of points and advance towards the rubber with a negative charge, while the glass which leaves it is positively charged. The rubber itself being negatively charged, it is clear that there will be attraction between it and the glass which leaves it, and repulsion between it and the glass approaching. On both accounts the electrical forces must produce a resistance to the revolving plate, or cylinder, and it is the equivalent of the work spent in overcoming this resistance which appears as the energy of the electrification produced in the prime conductor. In any actual case, however, the glass advancing towards the rubber will not be entirely free from a positive charge, but this residual charge will be much less than the charge on the part leaving the rubber, so that the attraction against the motion being more than that favouring it, there will be a balance of resistance requiring to be overcome.

Besides this resistance there is another, arising from the simple friction between the glass and the rubber. The work done to overcome this directly produces heat, which only warms the surfaces in contact, and is wholly wasted as far as the proper function of the machine is concerned. So great is this waste, in even the best machines of this class, that only a small fraction of the work spent in driving them produces the intended effect.

If multiplying gear be employed to increase the rate of rotation of the machine, the difference of potential between the glass and rubber is rapidly increased. But a limit to this increase is soon attained, when the attraction between the

opposite charges on the glass and rubber becomes so great that discharge takes place between them, instead of between the glass and the collecting points.

311. Another very simple and useful instrument for producing small quantities of electricity, and which depends, primarily at least, for its action on friction, is the electrophorus of Volta. This instrument has been already described (sect. 143).

In order to charge a conductor rapidly by means of the electrophorus, it would be necessary to adopt some mechanical arrangement whereby the insulated cover could be rapidly laid on and removed from the resinous plate, and alternately brought into contact with the metallic tray, and with the conductor to be charged. As, however, there would be nothing in the action of such an arrangement to replenish the original charge given to the resin, that charge would be soon dissipated, and all further production of electricity would cease, till the resin was charged afresh from an extraneous source. This is precisely what takes place in the Bertsch machine, represented in fig. 196.

In this machine we have a circular plate of vulcanite which can be made to revolve on a horizontal axis. At opposite extremities of a vertical diameter there are rows of collecting points, the lower of which we shall suppose is connected with the earth, while the upper is attached to an insulated prime conductor of large capacity. Opposite the lower row of points, and on the other side of the revolving plate from it, is placed a sector of vulcanite which has been negatively charged by friction with flannel. This sector is placed vertically, leaving a thin air space between it and the revolving plate. The negative charge on the sector acts inductively on the lower row of points through the air and revolving plate as a kind of compound dielectric. In consequence of this inductive action, the row of points deposits a positive charge on the part of the plate facing it, the corresponding negative charge having been repelled to the earth. When this positively charged part is brought, by the revolution of the plate, opposite the upper row of points, it gives up, through them, its positive electricity to the prime conductor,

and returns ready to receive a fresh charge from the lower row. By rapidly revolving the plate, the prime conductor

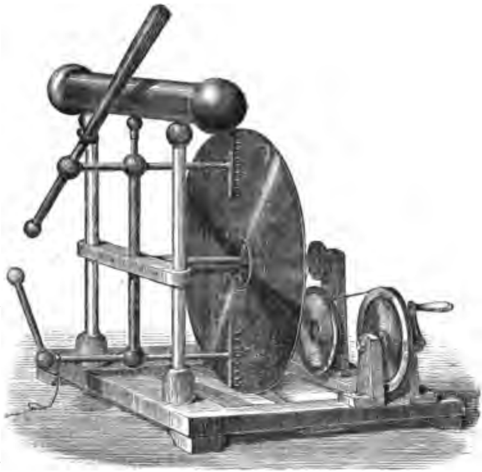


Fig. 196.

can be charged to a high potential, and a stream of sparks drawn from it to a body in contact with the earth.

In driving this machine, work has to be done to overcome the attraction of the opposite charges on the electrified sector and the part of the revolving plate which faces it. This attraction will become less and less as the initial charge on the sector gets gradually dissipated, through imperfect insulation, in consequence of no provision having been made in the machine itself for automatically replenishing this charge.

312. We come next to machines in which ample provision has been made for not only automatically replenishing, but increasing to almost any extent, the initial charge or difference of potential which is given to start them. Examples of such machines are Nicolson's Revolving Doubler, Varley's machine, the Replenisher and Mouse Mill of Sir William Thomson, and the Holtz machine. The action of all these

depends upon the same principle, which will be best illustrated by the description of a hypothetical arrangement.

Suppose we take four similar insulated discs of metal P, Q, R, S, and place them in order round a circle so that P and R may be at the extremities of one diameter, and Q and S at the extremities of the diameter at right angles to the former. Let us call P and R inductors, and Q and S receivers. Further, suppose we have a vertical axis passing through the centre of the circle and carrying a non-conducting cross-piece, to the ends of which are attached two discs similar to the former, which we shall call carriers, and designate by A and B. Let the cross piece and discs be so placed that while the axis revolves, A and B are brought successively opposite, and close to P, Q, R, S, but not into actual contact with any of them, except by means of light metal springs, with Q and S only. Before starting, let P and R receive opposite charges, so that their potentials may be represented by P and R respectively. When A is opposite to P, and B to R, let them be brought by springs into contact with the earth or with each other. Now, if the co-efficient of induction between the inductors and carriers be x, and their capacities each unity, A will move away from P with a charge xP, which it will give up by means of the spring to the receiver Q. Meanwhile B has left R with a charge xR, which it has similarly given to the receiver S. During the next half-turn, B will carry a charge xP to Q, and A a charge xR to S, so that at the end of one half-revolution Q will have a charge equal to xP, and S a charge equal to xR. The difference of potentials between the receivers at the end of one half-revolution will thus be x (P—R). Manifestly, after each half-revolution the difference will be increased by the same amount, so that it will augment in an arithmetical ratio.

It will be observed that the charges of P and R have meanwhile remained unchanged, unless in so far as they may have been diminished by imperfect insulation.

Suppose now that we connect, by a wire, the receiver Q with the inductor R, and the receiver S with the inductor P. It is obvious that this will be precisely the same as if we had originally made Q and R one plate of metal, and similarly

of S and P. We shall find, however, that, by this charge, the action of the machine is very much altered. Understanding that the initial charges of P and R are the same as formerly, let us follow the carriers in their rotation. A will leave P with a charge xP, which it will give up, by means of the contact spring, to R, thus rendering the potential of R, R—xP. Similarly, B will leave R with a charge xR, which it will give to P, and so make the potential of P, P—xR. In this way, after one half-turn, the difference of potential between P and R, instead of being P—R as at starting, will be P—xR—(R—xP), that is $(1+x)$ (P—R). Thus, if we know the difference of potential of the inductors after any number of half-turns, the difference after one more half-turn will be found by multiplying the former difference by the factor $(1+x)$. Thus P—R, being the initial difference, the difference after one half-turn, as we have seen, is $(1+x)$ (P—R); after two half-turns, it will be $(1+x)^2$ (P—R); after three half-turns $(1+x)^3$ (P—R), and so on, thus augmenting in a geometrical ratio. This explains why it is that, in machines of this class, an initial difference of potential, however small, gets rapidly multiplied to an enormous amount.

The replenisher (sect. 167), invented by Sir William Thomson, is almost identical in its action with the arrangement we have just described.

In the large machine of Mr Varley there are two metallic inductors fixed, at some distance apart, to an insulated plate. The carriers consist of pieces of metal attached to a circular sheet of ebonite, which revolves close to and facing the inductors. Pins are provided by which each opposite pair of carriers is brought, in passing, into contact with the inductors, and when fully under cover of the latter, each opposite pair of carriers is also put into contact with each other by means of a wire and contact springs. When the machine is in action, a copious supply of sparks can be drawn from either inductor, or a constant stream of electricity can be made to pass between them.

In the arrangement called the mouse mill, employed by Sir William Thomson, the carriers are attached to the surface

of an insulated cylinder which revolves between inductors forming parts of a concentric cylinder.

Certainly the most remarkable of all the machines which depend on the principle of electric induction is that designed by Holtz of Berlin, already described (sect. 149).

313. A most useful modification of the Holtz machine has been recently introduced by Töpler, which has the great advantage of not requiring any initial charge to start it.

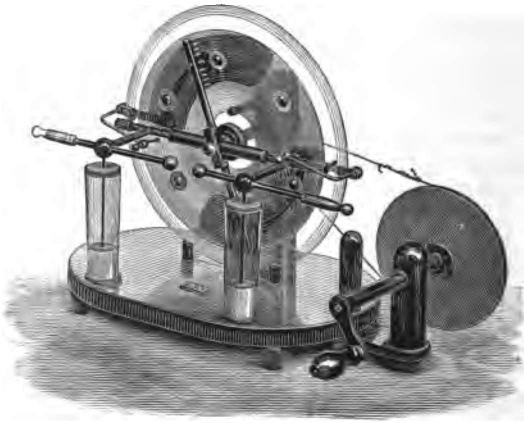


Fig. 197.

In this form of machine a number (usually six) of circular discs of tinfoil, about two inches in diameter, are pasted upon the surface of the revolving glass plate at equal distances from each other. To the centre of each disc a small hemispherical metallic button is attached, which, as the plate revolves, comes in contact with a set of metallic brushes. One pair of these brushes is attached, at opposite extremities of a diameter, to the stationary plate, and is in contact with the paper inductors. The other pair is in metallic communication with each other, and is fixed opposite the extremities of a diameter of the revolving plate. In connection with this last pair of brushes there are also rows of points similar to the usual rows of points in the Holtz

machine. The inductors are exactly similar to those of the Holtz machine, with the exception, that underneath each there are two circular discs of tinfoil, connected by a tinfoil strip, placed at a distance from each other equal to the distance between the similar discs on the revolving plate. In a dry atmosphere this machine will give readily sparks four or five inches long, without the trouble of initial charging. The machine is represented in fig. 197.

314. In all these machines work is done against the electrical attractions between the inductors and carriers, and as the electrical charges increase in a geometrical ratio, the attraction, and therefore the work required to overcome it, increases in a like proportion. This is well exemplified in the Holtz machine, when, after a few turns, the attraction between the plates feels like a distinct drag upon the revolving disc. With a plentiful supply of work there is no limit, other than imperfect insulation, to the difference of potential that might be produced by such a machine. Ordinarily, in fair working order, sparks of nine or ten inches are readily obtained from it. An interesting experiment, illustrating the transmission of power by static electricity, may be made with two Töpler machines. If chains be led from the spark-drawers of the one machine to those of the other, and one of the machines turned, the other immediately begins to rotate at a rapid rate.

315. We now come to the consideration of machines of the second class—namely, those for converting mechanical work into current electricity. These machines are either magneto-electric or dynamo-electric machines—the former being the name given to machines in which the magnetic field is due to permanent magnets; the latter, to those in which it is due to electro-magnets excited by the generated current itself. The action of all such machines depends upon the principle of current induction, discovered by Faraday in 1831. This was really the first step that led to the construction of magneto-electric machines.

Not long after Faraday's discovery, the first actual magneto-electric machine was constructed by Pixii of Paris. It consisted essentially of a fixed electro-magnet, in front of which

a permanent magnet was made to revolve, the poles of both magnets facing each other. As, in the course of rotation, each pole of the steel magnet is brought opposite to the iron cores of the electro-magnet, these cores will be rendered for a moment magnetic, and, in consequence, will induce a momentary current in the surrounding wire coils. At each half-turn the magnetism of the iron cores will obviously be reversed, so that we may look upon the machine as precisely doing at a rapid rate the following operations successively: first, inserting a magnet into the wire coils; secondly, withdrawing it; thirdly, inserting it with its poles reversed; and fourthly, again withdrawing it. There are thus, in one complete revolution, four momentary currents produced alternately in opposite directions.

Modifications of this machine were afterwards produced by Paxton and Clarke, who made the permanent magnet fixed, and caused the electro-magnet to revolve. They also supplied a commutator to their machines for the purpose of causing the current always to flow in one direction.

Very large machines on this same principle were constructed by Holmes of London, and Nollet of Brussels. These were used for producing the electric light in lighthouses, and also for the purpose of electro-metallurgy.

316. *Magneto-electric Machine.*—The general construction of a simple magneto-electric machine is shewn in fig. 198, which is one of the forms of Stöhrer's machines. NS is a fixed permanent magnet. BB is a soft iron plate, to which are attached two cylinders of soft iron, round which the coils C and D are wound. CBBD is thus the revolving armature. AA is a brass rod rigidly connected with the armature, and also serving as the rotating axle. F is a cylindrical projection on AA, and is pressed upon by two fork-like springs, H and K, which are also the poles of the machine. The ends, *m*, *n*, of the coil are soldered to two metal rings on F, insulated from each other. When the armature revolves, AA and F move with it. F, H, and K are so constructed as to act as a commutator, reversing the current at each semi-revolution. By this arrangement, the opposite currents proceeding from the coil

at each semi-revolution are so transmitted to H and K that these retain the same names. But for this, the effect of the current derived from one semi-revolution would be reversed by that proceeding from the next. H and K, however, change names with the direction of the rotation of the armature.

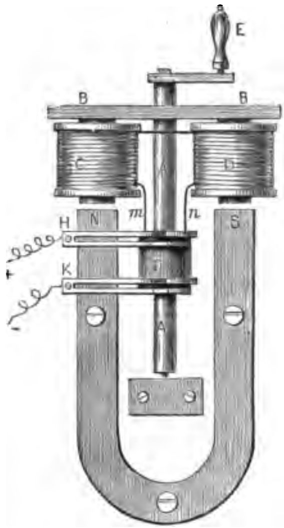


Fig. 198.

The commutating arrangement is shewn in fig. 199. A is the axis of the revolving part, the two black lines under H and K are the two forks of these springs, *a* and *f* are projections on a metal tube next the axis, and *c* and *e* are projections on another tube insulated by boxwood or vulcanite (shewn black in the figure) from the inner tube. Both tubes are fixed to the axis A, and move round with it. The projections *a*, *f*, *c*, *e* are half-rings, *a* and *c* being on one side of the axis, and *e* and *f* on the other. Each tube has the end of one of the coil-wires attached to it, so that the tubes thus form the terminations of the coil. As shewn in the figure, the left-hand prong of H rests on *a*, and the left-hand prong of K on *c*; if *a* be +, *c* will be −. Suppose, now, the half-revolution finished, then *b* will be on *e*, and *d* on *f*, just when the current has begun to flow in the contrary direction, and the tubes have changed signs. Still, however, H is + and K −. When the armature is made to revolve with sufficient rapidity, a very energetic and steady current is generated,

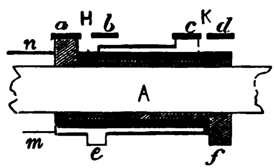


Fig. 199.

which possesses all the properties of the galvanic current. Compared with the galvanic battery, the magneto-electric machine is a readier, steadier, and cleanlier source of electricity, and is, in consequence, extensively used instead of it. Magneto-electric machines may be made of any strength by increasing the number of magnets and the mechanical force employed.

In the machine just described, the amount of electricity induced in the coils is at a maximum just when the armature is leaving the poles, and at a minimum when it stands equatorially. The gradual cessation of the magnetism of the core in the first quarter revolution, and the gradual acquisition of it in the second, prevents anything like an instantaneous stoppage and commencement of the current in the half-revolution. The current is thus tolerably continuous, and when the velocity is great, it is nearly uniform. Hence, when it is sent through the nerves of the body, which are affected by sudden changes of current strength, a slight effect only is felt. When, therefore, physiological effect is wanted, a break must be effected in the current. This is done in Stöhrer's machines by making the half-rings overlap a little, so that, at the change of pole, when the current is strongest, the interpolar resistance consists only of the prongs of each fork resting on the two half-rings. As this resistance is indefinitely small, the whole of the current goes by it, and none of it by the body. When one prong of each fork leaves simultaneously its half-ring, the current then passes through the body; and as the resistance of this last is great, a partial stoppage of the current occurs at the instant of separation, which excites an extra current in the coils of the machine. The tension of the extra current is high, and powerfully affects the nerves. It is felt at each half-revolution.

In large machines, several magnetic magazines are employed with a corresponding number of armatures and coils. The coils may be arranged like the cells of a galvanic battery, for tension or for quantity. For tension, they are arranged successively, so that they form one compound circuit; for quantity, each single coil or set of coils contributes to the common current. The electro-motive force, resistance, and

current strength are formed as for a galvanic battery. The thickness of wire is selected according to the object of the machine. For giving shocks, or effecting chemical decomposition, the wire must be long and thin ; for heating platinum wire, thicker and shorter. The electro-motive force increases with the rapidity of rotation. Dove has found that in magneto-electric machines, where the current is primarily induced by magnetism, a solid iron core as an armature gives a better effect than a bundle of iron wires.

317. *Siemens Armature.*—A very marked improvement in magneto-electric machines was made by Siemens when he introduced his new form of revolving armature (see fig. 202). This armature consists of a long bar of iron having somewhat the shape of a piece of an ordinary double-flanged rail. The wire is wound round it longitudinally in the hollow and over the ends, so that when finished the whole has a cylindrical form. This cylinder is made to revolve rapidly between the poles of a set of permanent magnets fixed astride it, and at equal distances from each other. A commutator is supplied for giving the currents one direction. The great advantage of this form of armature is, that it rotates in an intense magnetic field, and can be made to revolve very rapidly, and as a consequence proportionally increase the strength of the induced current. As yet, however, increasing the strength of the current depended entirely upon increasing the rate of rotation of the armature. Nothing had been done to increase automatically the magnetism of the magnets which induced the currents in the armature. This was reserved for Wilde, who adopted the ingenious plan of making the current from one machine, after it had been brought into the same direction by a commutator, to circulate round a plate of soft iron, which it converted into a very strong electro-magnet. This electro-magnet he used with another Siemens armature of larger size, the current from which, having been brought to one direction, was made to produce a still larger electro-magnet which acted upon a still larger armature. In this way, a current of enormous strength was finally produced, when sufficient driving power was employed. It is stated that a machine of this kind in full action was able to melt an

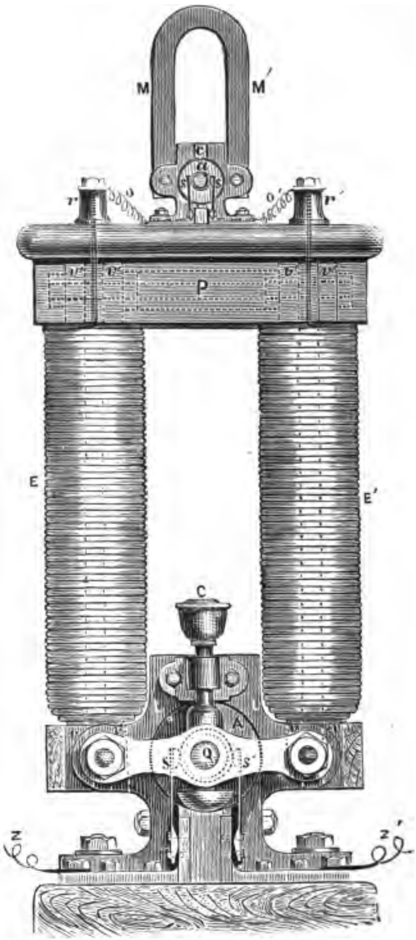


Fig. 200.

iron rod 15 inches long and a quarter of an inch in diameter, and produced a most brilliant electric light from carbon points.

318. *Wilde's Magneto-electric Machine.*—Fig. 200 shews a front elevation of a seven-inch machine. It consists of two separate machines—a purely magneto-electric machine, and a machine which is both electro-magnetic and magneto-electric. Both machines are in the main very similar, and in many respects identical, the only difference being in size and power. The smaller machine, MM′, which is purely magneto-electric, is seen surmounting the other. The horse-shoe permanent magnet, MM′, is the foremost of a series of sixteen similar magnets, placed the one behind the other in a horizontal row. Each weighs 3 lbs., and sustains a weight of 20 lbs. The sixteen magnets are fixed below to the *magnet-cylinder*, *c*, shewn on a larger scale in fig. 201. This is partly made up of cast-iron, partly of brass. The two iron components, *ii* (fig. 201), form the sides of it, and the brass bars, *bb*, lie between them. They are bolted firmly together by the brass bolts, *rr′*. The magnet-cylinder is about 12 inches in length; in the centre of it is accurately bored a circular hole, extending the whole way, $2\frac{1}{4}$ inches in diameter. The inner side surfaces of the magnets below are accurately fitted to the upright plane sides of the magnet-cylinder, and are firmly secured to it. By this means the cast-iron portions of the magnet-cylinder, *ii*, form the polar terminations of the magnetic battery, the brass bars, *bb*, between them, breaking the magnetic continuity.

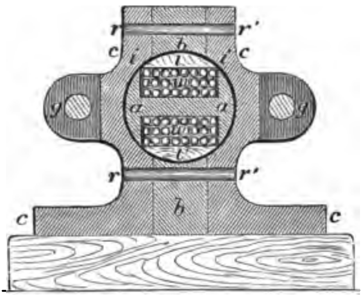


Fig. 201.

A Siemens armature, *aa*, of cast-iron is made to revolve within the magnet-cylinder. Its diameter is $\frac{1}{20}$th of an inch

less than the diameter of the cylinder, which enables it to revolve without friction in very close proximity to the polar surfaces. The manner in which it is centered is, for the sake of simplicity, not shewn in the upper machine, but it is shewn in the lower machine, where, as is afterwards mentioned, the construction, though larger, is perfectly similar. The framework for sustaining the axis of the armature is firmly bolted at *gg*. Fig. 201 gives, as just mentioned, an enlarged cross section; fig. 202 shews an enlarged side-view. Two rectangular grooves, *wl*, are made on opposite sides, giving to it somewhat the appearance of a rail. About 50 feet of insulated copper-wire, *ww*, is wound lengthwise into these grooves in three coils (shewn in section, fig. 201). The coil thus formed is shut in by wooden packing, *ll′*. In fig. 202 this packing is removed from the two ends to shew the longitudinal winding of the coil. To prevent the wires from being driven out by the centrifugal force generated in the rapid rotation of the armature, straps of sheet brass encircle the armature at regular intervals, and are sunk in grooves prepared for them in the cast-iron. Two caps of brass, *kk*, are fitted to the ends of the armature, and to these are attached the steel journals or axes of rotation, *ff*. On the further axis (the back axis of fig. 200) the pulley, *m*, is fixed, round which passes the strap from the steam-engine which works the machine. On the other axis (the front axis of the figure) two rings are put, one, *n*, insulated from it, and the other, *n′*, connected with it. One end of the armature coil is in connection with the armature, and thereby with the axis and *n′*; the other end is insulated

Fig. 202.

and fixed by a binding-screw with *n*; *n* and *n'* are thus the terminals of the coil. They are made of hardened steel, and the springs *s* and *s'*, which press against them are of the same material.

Starting from the position shewn in fig. 201, the armature in one revolution induces two opposite currents in the coil, one in the first, the other in the second half-revolution. It will be seen (fig. 202) that the separation between *n* and *n'* lies obliquely. In this way, each spring, *s* or *s'*, presses against a different ring at each half-revolution. As *n* and *n'* change their electric sign, it is so arranged that they change the spring, *s* or *s'*, against which they press. Thus *s* and *s'* receive their currents always in the same direction, consequently the wires, *o* and *o'*, convey the current away from the machine in a uniform direction. The armature is made to revolve 2500 times per minute, and 5000 waves or currents of electricity are transmitted to the wires, *o*, *o'*.

One advantage of this position lies in the motion of the armature not being resisted by the air. In the ordinary position of the armature, much of the work applied to the rotation is expended in the armature beating the air. There is no such loss in Wilde's machine. Another advantage is derived from the inductive action of the magnet being exerted directly on the coil, as well as through the intervention of the armature. If the coil were made to rotate without the armature, currents would be induced in it of the same kind as that induced by the armature, though of feebler intensity, the maximum points of which would occur when the coil was moving through the line joining the poles, and the minimum points when it was at right angles to that position. Now these are the converse of the maximum and minimum induction points of the armature. In the position in which the armature is placed in this machine, both armature and coil contribute to the current, the one most when the other gives least, and *vice versâ*. The same advantage is not secured by the ordinary construction.

We come now to describe the singular peculiarity and merit of Wilde's machine. The current got from the magneto-electric machine is not directly made use of, but is

employed to generate an electro-magnet some hundreds of times more powerful than the magnetic battery originally employed, by means of which a corresponding increase of electricity may be obtained. This electro-magnet, EE′ (fig. 200), forms the lower part of the figure, and by far the most bulky portion of the entire machine. It is of the horseshoe form, E and E′ forming the two limbs of it. The core of each of these, shewn by the dotted lines, is formed by a plate of rolled iron, 36 inches in height, 26 inches in length, and 1 inch in thickness. Each is surrounded by a coil of insulated copper wire (No. 10) 1650 feet long, wound round lengthwise in seven layers. The current has thus, in passing from the insulated binding-screw, *r*, to the similar screw, *r′*, to make a circuit of 3300 feet. Each limb of the electro-magnet is thus a flat reel of covered wire wrapped round a sheet of iron, the rounded ends alone of which are seen in the figure. The upright iron plates are joined above by a bridge, P, built up also of iron-plate, and are fixed below the whole way, along with the iron bars *v*, *v*, to the sides of a magnet-cylinder of precisely the same construction as the one already described. The iron framework of the electro-magnet is shewn by the dotted lines. The depth of the bridge is the same as the breadth of the bars, *v′*, *v′*, which are of the same size as the bars, *v*, *v*. The various surfaces of juncture in the framework are planed so as to insure perfect metallic contact. The upper and lower machines are in action precisely alike, only the upper magnet is a permanent magnet, and the lower one an electro-magnet. We have the same magnet-cylinder, I, I, the same armature, A, and springs, SS′, and the same poles, ZZ′: the size is, however, different; the calibre of the magnet-cylinder is 7 inches. The diameter of the lower armature gives the name to the machine—namely, a 7-inch machine. Figs. 201 and 202 are on the scale of the lower machine (fig. 200). The length of wire on the lower armature is 350 feet. It is 35 inches in length, and is made to rotate 1800 times a minute. The cross framework attached at *gg* to the magnet-cylinder, in which the front journal, *f*, of the armature rotates (at Q), is shewn in the lower machine (fig. 200). When the machine is in action, both armatures are driven simul-

taneously by belts from the same countershaft. For the electric light, the currents conveyed to the springs, S and S′, need not be sent in the same direction. In that case, the separation between *n* and *n′* is vertical; and each spring presses against only one ring during the whole revolution, receiving and transmitting each revolution two opposite currents. Oil for the journal and commutator is supplied from the cup C.

The machine here described is intended for a three-horse-power steam-engine, but more power might be expended on it. A larger engine could drive the smaller armature faster, and thereby cause much more energy to be expended, and more electricity to be induced in turning the lower armature than with a power of three horses. The machine, when worked with a power of three horses, will consume carbon sticks three-eighths of an inch square, and evolve a light of surpassing brilliancy. With a machine that consumes carbons half an inch square, a light of such intensity is got, that when put on a lofty building it casts shadows from the flames of street-lamps a quarter of a mile distant upon the neighbouring walls.

It will be observed that one peculiarity of all the machines hitherto noticed is, that the currents produced by them are alternately in opposite directions, and so necessitate the use of commutators. It remained as a desideratum to get a machine which would give continuous currents always in one direction. This was first clearly supplied, although only to a small extent, by the ring armature or transversal electro-magnet of Pacinotti. Pacinotti's machine was primarily intended to be an electro-magnetic one, although it did give continuous currents in one direction when driven the reverse way.

319. *Gramme Machine.*—It was not, however, till the appearance of the Gramme machine that we could be said to have a really efficient machine for producing continuous currents in one direction without the aid of a commutator. This machine is represented in fig. 203. The peculiarity of this machine rests in its armature, which somewhat resembles the transversal electro-magnet

of Pacinotti. It consists of a flat ring of say six inches or more in diameter, made of bundles of iron wire laid side by side. Grasping these bundles are a series of flat

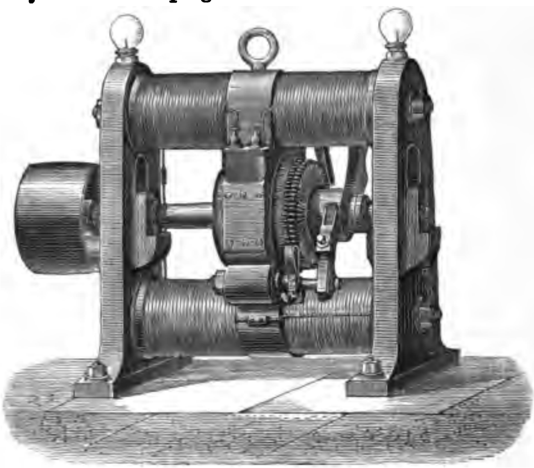


Fig. 203.

helices of insulated wire packed close together, sometimes as many as 64 helices being put upon one ring. These helices are all joined together so that a current can flow in the same direction round them all. The junction of each helix with its next neighbour is connected to a thin strip of copper, which is inserted edgeways into a cylinder of insulating material, which passes tightly through the ring. Passing through the centre of this cylinder is the metal rod on which the whole revolves. There are thus as many copper strips as there are helices, and care is taken that none of the grooves containing them communicate, either with each other or with the central axis. The insulated cylinder with its copper strips is turned accurately fair and smooth, so that it presents the appearance of a shaft striped longitudinally, and is such that springs pressing against it, as it revolves, come alternately into contact with a copper strip and with an adjoining insulated part. The whole is made to revolve close to, and

between the poles of a powerful electro-magnet, these poles being usually extended by having attached to them curved pieces of iron forming parts of a cylinder which, if complete, would closely envelop the ring armature. Two wire brushes press against the striped shaft at points opposite to each other, and in a line nearly at right angles to the line joining the poles of the electro-magnet. Attached to these wire brushes are the two terminals from which the current is received when the machine is in action.

That we may see clearly how it is that the currents produced by this machine are always in one direction, let us suppose that the iron wire core of the armature is fixed, and that the helices are made to revolve around it. This will evidently not alter in the least the actual action of the machine. Manifestly, by induction the iron wire ring will become magnetic, having its south and north poles respectively opposite to the north and south poles of the inducing electro-magnet, and having its neutral points at the ends of a diameter at right angles to that joining the poles. Let us also suppose that there is only one helix on the wire ring, and that it can be carried round the ring from a starting position opposite the north pole of the electro-magnet. Obviously, at starting, the helix surrounds the south pole of the iron ring, and in one half-revolution it passes from a south pole through a neutral point to a north pole, while in the second half-revolution it passes from a north pole through a neutral point to a south pole. Its motion may thus be accurately represented by supposing it to slide along a straight bar magnet from its south pole to its north, then to be turned round and sent back again, from the north pole to the south, with the same side in front on the return journey as was foremost at first. A little consideration will shew that in these circumstances the current induced in the helix always flows in one direction through a circuit joining its ends.

In the Gramme machine, no extraneous source of electricity is needed to sustain the current in the electro-magnet. This is done by the produced current being made to circulate through the coils of the electro-magnet. The small amount of residual magnetism is sufficient to start a feeble current.

This going round the electro-magnet, increases its inducing power, which again induces a stronger current on the armature, and this, in its turn, strengthens the electro-magnets. In this way the effect increases at each turn of the armature, according to the compound interest law, and at a rate, when the machine is going rapidly, which cannot be less than 600 or 700 per cent. per second. This explains why after a few turns the machine becomes so difficult to drive, and why there is hardly any limit to the strength of the current that can be produced by it, other than the amount of driving-power which can be employed.

Dynamo-machines for producing current electricity have been largely applied to useful every-day purposes. We have only to instance their application to produce the electric light which has now become so extensive. Machines of this kind have also been most successfully employed for purposes of electro-metallurgy.

Many other forms of dynamo-machines are in use at the present day, all depending essentially on the principles which have already been explained. The chief of these are the Siemens machine, the Brush machine, the Bürgin machine, and the large machine recently invented by Edison.

Electro-magnetic Machines, or Electromotors.

320. The function of these machines is to convert current electricity into mechanical work, and hence they may be regarded as the converse of the magneto-electric machines. In fact, almost all magneto-electric machines may be used as electromotors, by sending a powerful current from an external source through them. The forms in which they occur are exceedingly various, but a description of the simple apparatus illustrated in fig. 204, will suffice to explain their principle of working. NS is a fixed permanent magnet (it would do equally well an electro-magnet); the electro-magnet, *ns*, is fixed to the axis *ee*, and the ends of the coil are soldered to the ring *c* encircling a projection on the axis. The ring has two slits in it, dividing it into two halves, and filled with a non-conducting material, so that the halves are insulated from each other. Pressing on this broken ring, on

opposite sides, are two springs, *a* and *b*, which proceed from the two binding-screws into which the wires, + and −, from the battery are fixed. In the position shewn in the figure, the current is supposed to pass along *a*, to the half of

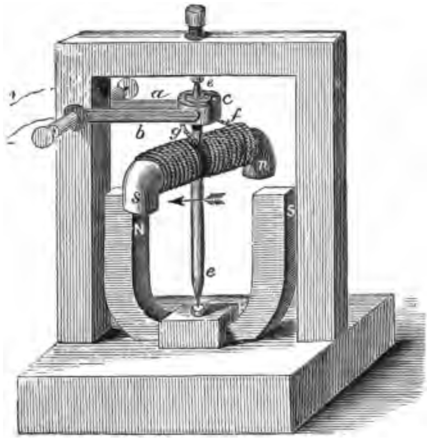


Fig. 204.

the ring in connection with the end *f*, of the coil, to go through the coil, to pass by *g* to the other half of the ring, and to pass along *b*, in its return to the battery. The magnetism induced by the current in the electro-magnet, makes *s* a south and *n* a north pole, by virtue of which N attracts *s*, and S attracts *n*. By this double attraction, *ns* is brought into a line with NS, where it would remain, did not just then the springs pass to the other halves of the ring, and reverse the current, making *s* a north, and *n* a south pole. Repulsion between the like poles instantly ensues, and *ns* is driven onwards through a quarter revolution, and then attraction as before between unlike poles takes it through another quarter, to place it once more axially. A perpetual rotation is in this way kept up. The manner in which a constant rotary motion may be obtained by electro-magnetism

being understood, it is easy to conceive how it may be adapted to the discharge of regular work. Powerful machines of this kind have been made with a view to supplant the steam-engine; but such attempts, both in respect of economy and constancy, have proved utter failures. It has been found that zinc cannot compete with coal as a source of mechanical action.

Jacobi was the first (1834) to construct such machines. In 1838 he constructed a machine of $\frac{3}{4}$ of a horse-power, by means of which he propelled a small boat on the Neva.

When a large quantity of mechanical work is required, the electromotors commonly used are the Gramme or Siemens machines, which are found to be perfectly reversible.

321. *Electrical Transmission of Power.*—Seeing that dynamo-machines and electromotors are now in such a state of efficiency, it becomes an important practical question how far they can be utilised as a means of transmitting power to a distance from one point to another. Such an idea must have occurred to many minds, but perhaps the first public expression of it as a practical application of electricity is due to Professor Blyth, who in 1872 wrote as follows: 'Magneto-electric machines might be employed to utilise the water power, at present running to waste, of mountain torrents, by first employing these torrents to generate current electricity by means of magneto-electric machines, and then transmitting that current by means of wires to drive an electro-magnetic engine wherever it was wanted.' The idea has taken practical shape in the hands of Sir William Armstrong and Siemens; and the power of distant waterfalls has been transmitted and made to drive sawmills, and do other useful work. Quite recently also, Siemens has shewn a tramway-car driven by one of his machines, the current being got from a similar machine worked by a stationary steam-engine in the neighbourhood of the tramway route. In this case, the drawing current was conducted to the electromotor placed below the car, either by means of the rails, or by means of conductors having sliding contact with two parallel conductors placed along the route, to which the current from the dynamo-machine was led.

CHAPTER XXV.

ELECTRIC TELEGRAPH.

322. The electric telegraph, like every other telegraph, aims at producing intelligible signals at a distance. The etymology of the word (*tele*, far off, and *grapho*, I write) implies that it is an instrument for writing at a distance ; but it has come to signify any means of conveying intelligence other than by voice or writing. The idea of speed is also implied—telegraphs being seldom, if ever, employed where they cannot transmit intelligence at a much quicker rate than can be done by the ordinary means of transit. There are three agents, which, from the rapidity of their propagation, are employed for telegraphing—sound, light, and electricity. Sounds, such as those of bells, guns, &c., form a convenient means of sending a single message through short distances. Light and electricity immeasurably exceed sound as ready, rapid, and certain means of telegraphing through long distances. Light, though an extremely rapid, is by no means a docile agent. It proceeds in straight lines, and will not bend round the ball of the earth, or inequalities on its surface. The semaphore, which was an ocular telegraph, and the only good one before the electric telegraph, illustrated this. Towers had to be erected in prominent positions, within sight of each other, and the signals, which were made by arms on the top of them, had to be retransmitted at every station. A large and well-trained staff was necessary to observe and transmit, and withal the work was slowly done. In foggy weather, moreover, the semaphore was useless. Electricity, which rivals light in speed, is most docile and trustworthy as a telegraphic agent. It silently wends its way in all weathers, over plain and mountain, across sea and land, and delivers its message in the office or parlour almost at the precise instant it was sent.

The various forms of electric telegraphs in general use are electro-magnetic. The signals are given by the deflection of a needle to the right or left, or by mechanism connected with the armature of an electro-magnet, which sways to and fro under the action of the magnet and a counter spring, or

between two opposite electro-magnets. Electro-chemical telegraphs have also been designed, but they have never come into permanent use. Electric telegraphs of all classes are of two kinds—those which merely give passing signals to the observer or listener, and those which permanently record their signals; the former may be called signalling, the latter recording telegraphs. The number of inventions connected with the electric telegraph is almost endless, and would engross a long series of volumes for their description. We shall here content ourselves with giving a mere outline of the working of the telegraph at present existing on most lines. The forms most in use everywhere at present are Morse's Telegraph and Cooke and Wheatstone's Needle Telegraph. For private use, some form of the magneto-electric dial telegraph is employed. In point of simplicity and certainty, Morse's system can scarcely be exceeded, and even as regards speed it stands equal, or nearly so, to the most rapid recorders. We shall therefore give an account of the general arrangements of a telegraph chiefly on Morse's system.

323. *Morse's Recording Instrument*, or as it is shortly called, the 'Morse' or 'Register,' is shewn in fig. 205. L is the line-wire, and E the earth-wire, conveying the current from the distant station. The current thus sent traverses the coils of the electro-magnet, MM′, the armature, A, of which is in consequence drawn down. A is attached to the lever *ll′*, moving round the axis *k*. By the attraction of A, the end *l′* is lowered, and brought against the stud *n*. The armature must not touch the soft iron of the electro-magnet on being drawn down, for if it did it would stick, and would not be instantly released when the current ceases. When the end *l′* is lowered, the end *l* is raised; *ll′*, at its inner end, carries a steel point or style, *p*, which by the upward motion is brought against a strip of paper, PP′, carried towards P′ by the rollers *rr′*, set in motion by clock-work, C, quite independently of electricity. The clock-work is liberated or stopped by the switch S. The paper is supplied from a large roll or bobbin, above the instrument, which turns round as the rollers demand. So long as the style is elevated, the paper strip is made by the clock-work to rub against it. A

line is thus embossed on its upper surface. To facilitate the doing of this, there is a groove in the upper roller, opposite the style. When the current from the distant station ceases, the lever *ll'* is pulled back to its original position by the

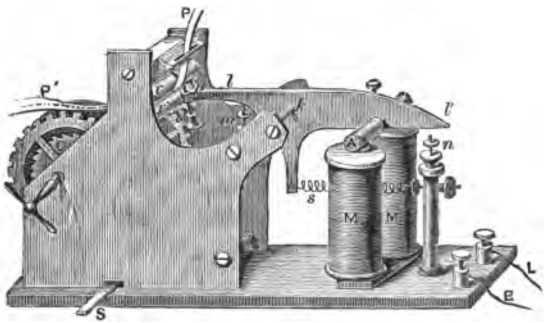


Fig. 205.

spring *s*, and the style falls away from the paper. To prevent it falling too far, another stud, *m*, lies on the other side of the axis. When the circuit is again closed, the style once more marks the paper, and thus the lever keeps oscillating under the opposing actions of the magnetism developed by the transmitted current, and the elasticity of the spring *s*. The time that the style remains elevated, determines the kind of mark on the paper. If it is nearly momentary, a dot is imprinted; for a longer time, a dash. We have thus the combinations of an alphabet in the combination of dots and dashes. The following is the usual Morse Alphabet:

A	· —	J	· — — —	S	· · ·
B	— · · ·	K	— · —	T	—
C	— · — ·	L	· — · ·	U	· · —
D	— · ·	M	— —	V	· · · —
E	·	N	— ·	W	· — —
F	· · — ·	O	— — —	X	— · · —
G	— — ·	P	· — — ·	Y	— · — —
H	· · · ·	Q	— — · —	Z	— — · ·
I	· ·	R	· — ·		

Thus A is a dot and a dash; B, a dash and three dots, &c.

The alphabet is so arranged that those letters occurring most frequently are more easily signalled; thus, E is one dot; T, one dash. An expert telegrapher can transmit from thirty to forty words a minute by this instrument on a land-line of between 200 and 300 miles. Several modifications of Morse's telegraph have been made, the principal of which is to substitute ink marking for embossing. The beautiful instruments of the Siemens and Halske are of this kind.

A clerk that has been well accustomed to a Morse telegraph, in transcribing, seldom looks to the paper. The mere clicking of the lever becomes a language perfectly intelligible to him. He need therefore only look to the record when he may have heard indistinctly. Sir Charles Bright does away with the recording instrument altogether, and substitutes two bells, one muffled, the other clear, sounded by a hammer oscillating between them. The bells speak a telegraphic language as quick as the clerk can write. Recording instruments are generally considered preferable to instruments which merely signal, as they fix any fault of transmission or copying on the party at fault. Acoustic signalling, again, is preferable to ocular signalling, as a person can hear and write much more easily than see and write.

324. *Transmitting Key.*—Let us now transfer our attention to the distant station, to see how the current is transmitted from it. This is done by the transmitting key shewn in fig. 206. A brass lever, *ll*, moves round the axis A. On opposite sides of the axis two nipples of platinum, *m*, *n*, are soldered to its lower sides. The nipple *m* is called the hammer. Below *n* is the stop anvil, *b*, tipped with platinum, which is in connection with the earth-wire E. Below the hammer, *m*, lies the anvil *a*, the nipple of which is likewise of platinum; *a* is connected by the wire C with one of the poles of the sending battery, gene-

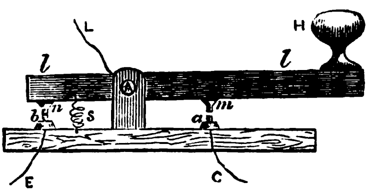


Fig. 206.

rally the copper pole. When the lever is left to itself, *n* and *b* are in contact under the force of the spring *s*. When the hand presses on the ebonite (insulating) handle H, contact is broken at *n* and *b*, and established at *m* and *a*. Three wires are in connection with the key, E and C just named, and L, the line-wire from the distant station, connected with the axis pillar, and therefore with the lever. When the key is in the receiving position, that shewn in the figure, the current from the sending station takes the route L, A, *l*, *n*, *b*, E, the Morse, then to earth. When H is pressed down, the key is in the sending position, and transmits the battery current by C, *a*, *m*, A, L, to the distant station. The play of the anvil and hammer need not be more than $\frac{1}{16}$th of an inch. This is more than sufficient for completely breaking the current, and it allows of speedy manipulation.

325. *The Battery.*—The batteries employed are in this country almost universally Daniell's. Constancy and certainty of action is what is most wanted in the battery, and these Daniell's battery yields. In Germany, Bunsen's battery is also used, charged with diluted sulphuric acid, the carbon being immersed in a mixture of 1 of acid to 10 of water, and the zinc in one of 1 to 20. When batteries have to be moved about much, sand is put in to keep the liquid from spilling. The number of cells employed varies with the distance, the insulation of the line, and the delicacy of the instruments. The register, as afterwards mentioned, is seldom worked directly by the transmitted current, but by relay. To work a relay with good insulation, 60 Daniell's cells will suffice for a distance of 300 miles. For less distances, less of course will suffice. For short circuits, where the resistance is small and current strong, small cells soon exhaust themselves; large cells therefore must be used to maintain the supply. Magneto-electricity is also employed as a source of the current. This answers well on short circuits, or for private telegraphs, but experience has proved that the galvanic battery is by far the most advantageous source of electricity for extensive telegraphic work.

326. *How Two Stations are connected together.*—The manner in which two stations are 'joined up' on Morse's system is

shewn in fig. 207. B and B_1 are the batteries at the stations S, S_1; *k*, *k'* are the transmitting keys; *n*, *n'*, the registers; *g*, *g'*, the galvanometers; LL the line-wire insulated on posts; P, P_1, the earth-plates. When the key *k*, at the station S, which is here represented as the sending station, is depressed, the current from the battery B takes the following course. From the copper pole C, of the battery B, it goes to the anvil of *k*, passes through *k* to the galvanometer *g*, which having

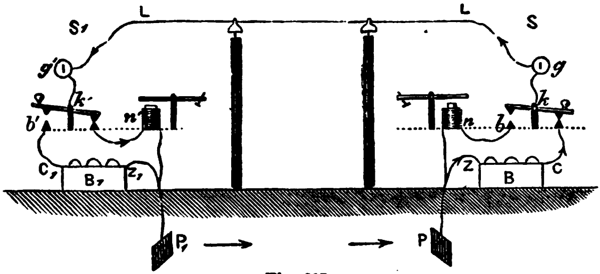


Fig. 207.

traversed, it goes into the line LL to the receiving station S_1, traverses the galvanometer, the key *k'*, the coils of the register *n'*; thence it goes 'to earth' at the plate P_1, returns by the ground to P at the sending station, and thus finally reaches the zinc pole Z of the battery B. At station S, *b* and *n* are out of circuit; and at S_1, *b'* and battery B_1 are out of circuit; *n* is thrown out of circuit, because its coil offers a resistance equal to several miles of the line-wire, and it is requisite to keep down the resistance to the minimum. If it were in circuit, both registers could print simultaneously, but that is not necessary, one record at the receiving station being enough. The sender would thus have no idea as to whether his message had told or not, did not the motions of the needle of the galvanometer, *g*, reveal the currents put in circuit. The galvanometer also shews the presence of earth-currents on the line. If *k* were left to itself, and *k'* depressed, the station S_1 would then be the sending and S the receiving station, and the connections would be exactly as shewn in the figure, only at opposite stations.

Suppose the clerk at S wishes to telegraph to S_1, he depresses the key *k* several times, so as to send a series of dots and dashes giving the name of the station. The attention of S_1 is first arrested by the clinking of the armature of the Morse. He thereupon turns the switch S (fig. 203), and sets the clock-work in motion, and sends back to S that he is ready, and the printing thereupon begins. When both keys are depressed, the whole circuit is broken, so that when both sender and receiver have their hands on their respective keys, no message can be sent. One might fancy that confusion would arise from cross messages, but clerks soon get over this inconvenience, and communicate back and forward with perfect facility. There is a code of working signals to indicate the kind of message, 'repeat,' 'understand,' &c., besides numerous recognised contractions. To arrest the attention of attendants, the current is sometimes made to ring an alarum bell.

327. *The Line.*—Telegraphic stations must be united by one insulated wire, carried over land, under ground, or under the sea. The insulation of land-lines is insured by attaching the wires to insulators fixed on posts some 20 feet high. The posts are placed at distances corresponding to the number of wires they have to carry. A distance of 80 yards is the ordinary distance for posts sustaining several wires, and 150 yards for those only supporting one. Insulators are of all shapes. Porcelain, though a better conductor than glass, is not so apt to attract moisture, and is the substance generally employed for them. The insulator known as Andrew's Insulator, shewn in section (fig. 208), is said to be very effectual. A bolt of iron, I, fixed to the cross-beam, *w*, of the telegraphic pole, is cemented into the ebonite cup or bell *ee*, which in turn is cemented into the porcelain bell *pp*. The porcelain bell acts as an umbrella to keep the wood to which it is fixed dry and insulating; that failing, the inside of the two cups is likely to remain dry and maintain insulation. The line-wire is kept fixed by binding wire into the groove *a*. The electricity has thus to

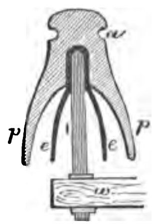


Fig. 208.

travel over the outside and inside of both cups before it reaches the iron bolt, which is also coated with ebonite. Such insulators as the one described cannot be used in railway tunnels, as they get coated over inside and out with engine smoke, which, being conducting, quite impairs their efficiency. The leakage in a long line, notwithstanding the best insulation, is considerable. The loss at each post is insignificant, but when hundreds or thousands are taken into account it becomes decided, so that merely a fraction of the total current that sets out reaches the earth at the distant station. In rainy, and more especially in misty weather, the insulation suffers much.

The wire most employed for telegraphic circuits is No. 8 ($\frac{1}{8}$th of an inch), but some companies are beginning to use No. 4 wire on some of their long trunk lines.

328. *A Submarine Line* is made by a cable. The core of the cable consists of one wire, or a strand of several wires of copper, as pure as can be got in the market. One solid wire is preferable to a strand of the same diameter in point of conducting power; but a strand is surer; for when one wire is broken at any point, the others still remain to conduct the current; there is no 'breach of continuity.' When the one solid wire gets broken, which not unfrequently occurs without being visible outside, the cable becomes useless. The strand of wire is generally laid up in Chatterton's compound, consisting of gutta-percha and resinous substances. The interstices between the wires are thus filled up, and this makes the cable solid throughout. It not unfrequently happens, when this precaution is not taken, that water, under the great pressure of ocean depths, becomes injected into them. The strand thus laid up, is now included in one or more coatings of gutta-percha, which acts as the insulating protection for the wire. Chatterton's compound is generally put between the layers of gutta-percha. The whole is finally included in a sheathing of iron wire, laid on spirally, to give the cable sufficient strength to withstand the strain of paying out, or that to which it may be subjected by the inequalities of the ocean bed. Between the iron sheathing and the gutta-percha, a layer of tarred yarn is put, which acts

as a padding between the two, and improves the insulation of the cable. Not unfrequently the iron wire of the sheathing is also protected from corrosion by tarred hemp. Fig. 209 (full size) shews the construction of the Malta and Alexandria cable, which is 1330 nautical miles long. The different layers are so far peeled off to shew the construction. C is a strand of seven copper wires, laid in Chatterton's compound; G, three layers of gutta-percha, with Chatterton's compound between each; H, tarred yarn; and I, the eighteen wires constituting the sheathing. The diameter out in the sea is 0·85 of an inch. Near the shore, the sheathing is made much stronger, to meet the danger of accident from the dragging of anchors.

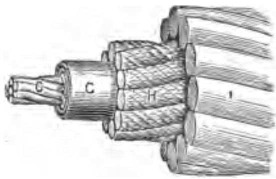


Fig. 209.

Considerable dispute has arisen as to the best material for insulating marine cables. India-rubber and gutta-percha are the two rival substances. It may be said in favour of gutta-percha that not one yard of it, when laid, has decayed; and that, under ocean pressures, as proved by the Atlantic cable of 1865, its insulating power decidedly improves. In favour of well masticated india-rubber, it is urged that cables, alike in other respects, will, when coated with it instead of gutta-percha, be capable of sending twice the number of words per minute, the specific inductive capacity being so much greater for the latter than for the former substance. On the other hand, india-rubber is not so trustworthy in point of durability, some specimens of it having become treacly after immersion for some time in the sea.

329. *The Earth.*—Two wires are not necessary to connect two telegraphic stations, as might be supposed. One wire is quite sufficient, provided its terminations be formed by large plates sunk in the ground, or something equivalent. The plates are generally of copper, and should not offer a surface less than twenty square feet, and they must be buried so deep that the earth about them never gets dry. The gas and

water pipes in a town make an excellent 'earth' (earth connection). The great object in an 'earth' is to put the whole ground in the neighbourhood in connection with the battery pole or line-wire, and much the same precautions must be taken in making an earth for a telegraph as for a lightning-conductor. If the earth is not good, the current, instead of taking the ground as a passage to the distant station, runs into other wires connected with the plate and leading to where the 'earth' is good. When the 'earths' are good, the current passes through the earth between the two stations, no matter what be the nature of the country it has to pass, plain or mountain, sea or land. The earth resistance to the current, compared with that of a long line, is next to nothing. The earth not only serves the purpose of a second wire, but of one so thick that its resistance may be left out of account, and thus halves the resistance of the whole circuit. It is a question whether the current actually travels between the two stations, or whether an equal amount of opposite electricity becomes simultaneously lost at each. This question cannot be decided, as the electric conditions in either case are identical. In conducting power for equal dimensions, the earth stands much inferior to the wire; but then its thickness, so to speak, is indefinitely greater, and hence its superior conducting power on the whole. One good 'earth' serves for all the circuits of a telegraphic station.

330. *Return Current—Inductive Embarrassment.*—When the line-wire at a distant station is 'cut' (insulated or disconnected with the ground), and is placed in connection with one of the poles of a battery, the other pole of which is to earth, at the instant in which the connection is made, a current flows into the wire, and if the insulation of the line be perfect, almost instantly ceases. The needle of the galvanometer makes a sudden deflection, and then returns to its position of rest. If now, at one turn of a commutator, the battery connection be cut off, and the line be put to earth, the needle deflects momentarily in the opposite way, and the charge given to the wire returns and goes to earth. This flowing back again of the charge is called the ***return***

current. In land-lines the return current is very slight, in submarine cables it is very marked. The return current shews that a telegraphic line may be charged statically, just like the insulated balls, cylinders, &c., illustrating frictional electricity. A line of telegraph may be looked upon as a Leyden jar, the wire as the inner coating, the air or gutta-percha as the glass or dielectric, and the earth or sea as the outer coating. A coil of submarine cable, immersed in a trough of water when the core is insulated, may be charged and discharged exactly as a Leyden jar, the water being the outer coating. The return current is most marked in long lines. In such it is not necessary to 'cut' the wire, the great resistance of the long wire being equivalent to partial insulation; the return current being, however, much smaller in extent.

The statical charge, of which a line of telegraph is thus capable, shews that the electric force not only tends to propagate itself longitudinally, but laterally. The effect of lateral induction is to retard the time of delivery of a signal, and to prolong it, so that, although it is a momentary signal at starting, it becomes a prolonged signal at its destination. Wheatstone's calculation gives a velocity of 288,000 miles per second for electric discharge. If signals were propagated at this rate, the time elapsing between the sending and delivering of a current, even on a line extending over one-half the circumference of the globe, would be inappreciable. But in aërial lines of land telegraphs, even only a few hundred miles in length, there is evidence that electricity does not propagate itself at anything like that speed, and in submarine cables the velocity scarcely reaches thousands of miles per second. The mere slowing of the message would not matter so much, provided the signals, when they reached their destination, were told out as they were sent. But they are not. Each signal at the receiving station takes a longer time to leave the line than it did to enter it. Hence, in a very long land-line, or in a cable, if the sender transmitted at the same rate as he does in short circuits, the signals would run into each other at the receiving station, and be undistinguishable. Time must be given to allow each signal

to ooze out of the cable before another is sent. The effects of lateral induction on the transmission of telegraphic currents constitute what is termed *inductive embarrassment.*

According to Sir William Thomson, the maximum speed attainable on an aërial land-line of 2000 nautical miles in length, and consisting of an iron wire one-fourth of an inch in diameter, would be 20 words per minute. The same authority has established that *the retardation increases with the square of the length of the line.* Accordingly, on a line 1000 miles in length, the number of words would be 80; on one 500 miles, 320; and so on. Direct lines are not worked for distances greater than 1000 miles, and very seldom even for the half of that distance. The maximum speed of telegraphing on short circuits has been 50 words; so that on a line 1000 miles in length and one-fourth of an inch thick, there is still a wide margin before the lateral induction would interfere. Most land-lines, however, are not more than one-eighth of an inch thick, and in them the embarrassment would be felt nearly four times as much as in the line just mentioned. On a line 1000 miles in extent of No. 8 wire, it would be advisable to break the circuit half-way, and re-send at the mid-station by translation. The whole would thus be worked as two circuits of 500 miles, and the speed of signalling could be four times increased. The maximum speed of signalling through the 2000 miles of the Atlantic telegraph of 1858 was two and a half words a minute. The copper core had a conducting power somewhat higher than a No. 4 iron wire. According to the law of squares, if the cable had been 1000 miles, the rate of signalling might have been increased to 10 words; if 500 miles, 40 words; and so on. If the ratio of the thickness of the core to that of the insulating coating be kept the same, the number of words that can be sent varies as the amount of material employed, or as the square of the diameter of the cable. Thus, if a cable be of the same make and of equal length as another, but twice as thick, four times as many words may be sent by it. The thickening of the core alone is not all gain in the way of lessening embarrassment, for while the conduct-

ing power of the core increases with its section, the lateral induction increases with its circumference.

Numerous explanations have been given of inductive embarrassment. We may suppose the charge at starting to have two inductive channels to reach the ground, one through the core to the further end of the cable, and the other through the gutta-percha. Electricity, when it has two channels, acts through each in the proportion of the facility offered it. If the gutta-percha were thick and the core short, the facility offered by the latter would be indefinitely greater than that offered by the former. There would be then no lateral induction, for the electricity would keep to the core. But when, as in long cables, it has some hundreds of miles of core and a quarter of an inch of gutta-percha to work through, the rival channels stand more nearly on a par. At each point the part of the electricity sent in to the cable acts inductively through the gutta-percha, and the rest acts in the line of the core. This last is subject to this diversion as it moves along; hence, if the cable be long, the whole is for the instant absorbed in charging the cable statically, and possibly only a part at a time. Such being the case, the further progress of discharge is effected not immediately by the force of the transmitting battery, but by the polarity induced by it in the particles of the dielectric gutta-percha. The effect is somewhat the same as would be experienced in sending a charge of water through a pipe filled with the same, whose sides, though water-tight, were elastic. If the pipe be long and narrow, and the friction of the water against the sides consequently great, on the charge being injected, the pipe on the sending side yields, and the further transmission of the charge is effected by the elastic force of the sides. The charge travels as a wave to the other end, and its delivery is thereby retarded and modified. This temporary yielding resembles the inductive diversion of the charge to the gutta-percha.

In aërial lines the lateral channel, the air, which is some twenty feet thick between the wire and the ground, offers much less facility for inductive action than in gutta-percha cables. The lateral induction is consequently very much less. In insulated subterranean lines it is nearly as much as in

submarine cables. They are consequently never used except for short distances, where they are unavoidable.

There is as yet no way of obviating lateral induction in telegraphic cables, except a thick core and a thick layer of insulating material. This is tantamount to saying there is no cure at all; for in very long lines, where it is most felt, a thick cable cannot, from mechanical difficulties, be laid. There are several ways, however, of diminishing it. A material, such as india-rubber, whose specific inductive capacity is low, lessens the evil considerably. The tarred hemp used in cables also reduces the lateral induction. Some have suggested the use of a double wire in the cable, the second wire supplying the place of the earth. This has, however, been found to aggravate instead of lessening the evil. The use of electricity of high tension, such as that of induction coils, has also been tried. That such passes with greater despatch may be open to doubt, and that it is dangerous in causing the charge to puncture the gutta-percha, and thereby destroy the cable, is highly probable. A transmitting key was used in the Atlantic expedition of 1865, which had a double action. It first placed the cable in connection with one of the poles of the battery, and then with the ground. The first connection charged the cable, the second allowed discharge to take place at both ends of it. By this key the number of words was increased by one-half.

The insulation of submarine cables is almost perfect, so that inductive embarrassment must not be confounded with leakage. The insulation of the Atlantic cable of 1865 was so perfect, that when 'cut' and charged, it took 15 minutes to fall from charge to half-charge.

331. *Earth Currents.*—These are very unwelcome visitors in telegraphic offices. They arise from different parts of the earth, being, from some unknown cause, at different potentials. They flow sometimes in one direction, sometimes in another, change rapidly, and are frequently so strong as to render the line for the time quite useless. They occur simultaneously with magnetic storms. The famous magnetic storm that raged on August 2, 1865, at the same time that the Atlantic cable ceased to act, was accompanied by earth currents

so strong that the Astronomer-royal considered it impossible, even if the cable had been perfect, to have signalled through it. One remedy for earth currents is to do away with the earth circuit, and put two wires to the same place in one circuit. Although the earth current runs equally strong in both, the two wires bring it to opposite ends of the instruments at the stations, and its effect is thereby neutralised. This, of course, can only be done where two wires exist. Another remedy is to use condensers, and work with an interrupted circuit. Little or nothing is as yet known of the laws regulating such currents.

332. *Relay.*—Hitherto we have supposed that the recording instrument of Morse is worked directly by the line current. This is only done on short circuits, generally less than 50 miles. On long circuits, direct working could only be accomplished by an enormous sending battery. The loss by leakage on the way is very considerable, so that a current strong at starting loses greatly before it reaches the station intended ; besides, the leakage becomes all the greater the greater the number of cells employed, or the greater the tension of the battery. It is found a much better arrangement to get the 'Morse' worked by a local current, which may be made as strong as requisite without any loss, and to include a very delicate instrument in the line circuit, which has only to make or break the local circuit. Such an instrument is called a relay, the principle of the action of which is shewn in fig. 210. Instead of the electro-magnet of the register being in the line circuit, the electro-magnet, E, of the relay is included. The coil is long, and of thin wire, and a very faint current is sufficient to develop magnetism in the core. The line current passes through the coils of E just as it is represented doing through that of the Morse in fig. 205. The armature of the relay, A, is attached to a lever, ee', moving round the axis a. When a current is sent through the coil, the lever is drawn down, and the end e' rests on the screw S. When there is no current, the elasticity of the spring s brings it back against the screw S′. The spring, s, is so adjusted that the play of ee' may be made as easy or stiff as the strength of the line current requires. The

pillars N and P are connected with the poles of the local battery. The metal spring *s* places the lever *ee'* in conducting connection with P. The poles of the battery may therefore be taken to be the screw S, and the end *e'* of the lever. When these are in contact, the local current flows, and it stops when *e'* is brought back against the insulated screw S'. The Morse is included in the local circuit. When a current comes from the sending station, the armature, A, is attracted, *e'* falls on S, the local circuit is closed, and the Morse begins to print. When the current ceases, *e'* falls on S', and the style of the Morse is withdrawn from the paper. The effect is thus the same as if the line current printed, and not the local current. By this means, a current that would have no effect on the Morse, can complete the local circuit, and print most legibly.

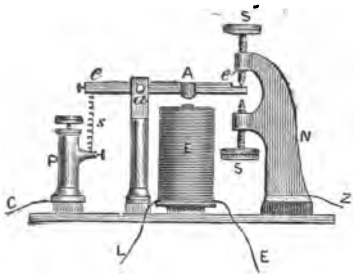


Fig. 210.

333. *How several Stations are connected in one Circuit.*—This is effected in three ways—by an *open circuit*, by a *closed circuit*, and by *translation*. In all of these, each station may telegraph simultaneously to all the stations in the circuit, and if the message concerns them all, a record may be printed at each station. When a station wishes to telegraph to another, it keeps signalling the name till the station in question signals back that he is ready. The others, finding that the message does not concern them, leave the two concerned in possession of the circuit.

The arrangement of an intermediate station in an open circuit is shewn in fig. 211. L_1 and L_2 are the wires from the terminal stations; R is the relay; the rest mean the same as in fig. 207. The station is represented as receiving. The line current passes through the key, the relay R, and goes on to L_2. The relay sets the local battery and the

register in operation. The line current is brought into the station, and led out without being affected. Electrically, it is the same as if it had gone on in the air direct from L_1 to L_2. When the station sends, the key is depressed. The current goes from C into the line L_1, is earthed at the one terminal station, leaves the earth at the other, and returns by Z to L_2. The battery here has no 'earth,' as at the terminal stations, the arrangement of which is as in fig. 207. An 'earth,' however, is generally put at each station, so that it may be worked as a terminal station if required. R at sending is out of circuit. According to this plan, every station must have a battery as strong as the terminal stations. In the closed circuit, no battery is needed at the intermediate station. If the battery and its connections be removed, fig. 211 gives the arrangement in a closed circuit. The battery may be placed only at one terminal station, or it may be divided into two, and a half put at each end—both, however, being joined up to act with, not against each other. The circuit is closed when no one operates, so that a current constantly flows. The keys breaking the connections stop it for the time. The relays act negatively, making the Morse print when there is no line current, and be at rest when it flows. If S′ in the relay (fig. 210) were uninsulated, and S insulated, it would act in a closed circuit. The advantage of the closed circuit is, that the batteries which require considerable attention are confined to the terminal stations, where they can be best cared for. Besides, little or no adjustment is needed for the relays. In the closed circuit, all the relays are in circuit at once. Open and closed circuits are used in lines where a number of smaller towns are joined together, the business of all of them being no more than sufficient to keep the line working. They are for short distances, seldom more than 200 or 300 miles.

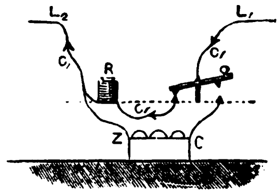


Fig. 211.

When two stations, say 500 miles apart, are to be connected

by telegraph, it is seldom done by a direct line, it being found more efficient to transmit to a half-way station, and thence to retransmit to the end one. The retransmission is effected not by manipulative skill, but by mechanical contrivance, so that, while the half-way station may read the message sent, no time is lost in the transmission, and the two end stations and the intermediate station communicate with each other as readily as if they were in an open or closed circuit. This mechanical retransmission is called *translation*. It is effected by making the lever of the register act as a relay in transmitting a message to the next station. The system, to be fully explained, would require more detail than we can here give to it. We shall only shew how translation can be effected, leaving out of account how all the stations can communicate as in one circuit. We also suppose, for the sake of simplicity, that no relay is needed, and that we are dealing with a direct working register. The current, C_1 (fig. 212), from the sending station enters the coil of the register M, and goes thence to earth P, and returns as shewn by arrow C_1. The register may record or not, according to the message, but its doing so or not in no way interferes with translation. The copper pole, C, of the battery is connected with the lever ll' of the register, and the zinc pole is to earth. When the lever is drawn down by the current, C_1, it strikes against the point at the top of the pillar p, that checks its motion. The pillar p is joined to line L_2, running to the further station, and when the lever falls, a second circuit—namely, that of the battery—is closed, in which C, the lever, the pillar, L_2, the further station, the earth, P, and Z are all included. Thus, as ll' prints at the intermediate station, it at the same time sends a new printing current to the next. When it ceases to print, so does the register at the distant station. It is in this way that parliamentary news is transmitted simultaneously to all

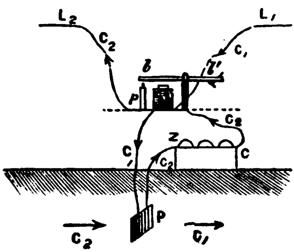


Fig. 212.

the important towns lying between London and Aberdeen. At the shore ends of submarine cables there is always a translating apparatus. This allows the cable to be worked by a battery suited to it, without loss of time in making it a special circuit. As an example of translation, it may be mentioned that the Indo-European line from London to Teheran, a distance of 3800 miles, is worked by five repeaters without any retransmission by hand.

334. *Cooke and Wheatstone's Needle Telegraph.*—This consists of an upright galvanometer, with the astatic needles loaded at the lower end to keep them, when not acted on, in a vertical position. A front view of the single-needle instrument is given in fig. 213, and a back or interior view in fig. 214. One needle moves within the coil OO, and the other on the face of the dial. It is the dial needle which acts as the indicator. The alphabetical code is made up by combinations of the right and left deflections of the needle. The old alphabet is given in fig. 213. A is made by two left deflections, M by one right; D by one right, then one left; R by one left, then one right; G by two right, and one left; and so on. The short arm indicates which beat is made first, and the long that made second. The telegraph companies now adopt an alphabet corresponding to Morse's code, a right-hand deflection corresponding to a dash, and a left-hand deflection to a

Fig. 213.

dot. The instrument is so arranged, that when the handle, H, stands erect, the whole is in the receiving state. When the handle turns to the right or left, the instrument sends, and the needle deflects accordingly to the left or right at both the sending and receiving stations. The instrument (fig. 214) has four connections: L, the line wire; E, the earth wire; C, the copper pole of the sending battery; and Z, the zinc pole. It is represented in the receiving position. The current takes the course L, *a*, the coil T, the spring *cd*, the metal points in the pin *p*, the metal spring *ef*, thence by *g* to earth. The handle in front works the cylinder PIN, which turns on the axis *n*. It is divided into three parts: those marked P and N are covered with copper, and are insulated from each other by the intermediate part, I, which is of ivory. By the spring *st*, which presses against it, P becomes the + pole of the battery, and by the spring *mi*, through the axis *n*, N becomes the — pole. A metal tooth, *k*, is fixed to P, and another, *h*, to N. These stand vertical, and are out of circuit when the instrument is in the receiving position. When a zinc (reverse, or negative) current is put to line, the handle, H, is so turned that *h* presses against the spring *dc*, and removes it from the point at *d*, thus breaking the receiving circuit. At the same time that *h* presses on *dc*, *k* presses on *or*. The reverse

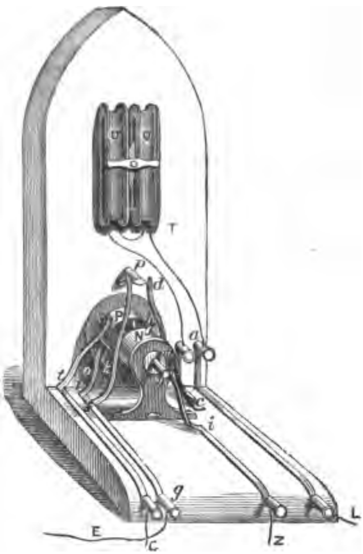


Fig. 214.

current takes the following course: Z, *i*, *n*, N, *h*, *c*, coil, *a*, L, distant station, earth, E, *g*, *r*, *o*, *k*, P, *s*, *t*, C. When the handle is turned the opposite way, *h* presses against *ef*, and *k* against another spring similar to *or*, on the other side of P, which is not shewn in the figure, and which is connected with the strip of metal *c*, and thereby with OO, and the copper (or positive) current is put to line. The cylinder PN acts as a commutator, sending a copper or zinc current, according to the side towards which it is turned. Sometimes two needles are placed in the same box, each having a separate line-wire to work it. The telegraphing can be much more expeditiously done with two needles than with one, as two deflections can be made at once, one on each instrument. The rate of signalling with a double needle is rather above what can be done by a Morse. Seeing that two wires are necessary for a double-needle instrument, and that only one is necessary for a Morse, it is a much more expensive instrument. Single-needle lines are much used for working railways, and for circuits with little traffic, but not for main telegraphic lines. The needle instrument is delicate enough to be worked direct without a relay. The dial of these instruments is movable, so that when earth currents deflect the needle to a position from the vertical, the stopping pins still stand at an equal distance on each side of it. When several stations are joined on the needle system, the open circuit arrangement is employed.

335. *Reflecting Galvanometer and Siphon Recorder.*—For signalling through long submarine circuits such as the Atlantic cable, the reflecting galvanometer (sect. 270) is the only instrument which has as yet been found practically successful. When so used, it really becomes a single-needle instrument whose index is a spot of light. By the right and left movements of this spot of light across a paper scale, the signals are made out; and the instrument is of such delicacy, that even a feeble working current, notwithstanding the length of the circuit, can make these movements quite distinct. Condensers are employed to annul the effects of earth currents.

For recording messages through long submarine circuits, Sir William Thomson has also invented a very delicate

instrument called the Siphon Recorder. It is so called from one of its essential parts, which consists of a fine light glass siphon, so hung that its shorter leg dips into a cistern of ink, while its longer leg comes close to, but without touching, a strip of paper, paid out by clock-work at a uniform rate. When a message is being sent, the point of the siphon tube is made to vibrate backwards and forwards in a direction transverse to that in which the paper is moving. This motion is given to it by means of a delicately suspended rectangle of wire with which it is in connection, and which hangs, when at rest, with its plane axially between the poles of a strong permanent or electro-magnet. The working current passes through this rectangle, and according to its direction causes it to rotate through a small angle to the one side or the other. In order that the point of the siphon may move across the paper without friction, and yet leave an ink trace, the following ingenious arrangement is adopted. The cistern of ink in which its shorter leg dips, is kept constantly electrified by means of a small electro-static induction machine, and in this way the electrified ink is constantly spurted out upon the paper in a fine stream. The letters of the message are made out from the ink trace, which consists of a series of connected angular-hand strokes extending to greater and less distances on one side or the other of the middle line of the paper, according to the direction and duration of the currents sent to line at the transmitting station.

For a full description of this instrument, as well as for the methods of automatic, duplex, and quadruplex telegraphy, we must refer to treatises on Practical Telegraphy.

CHAPTER XXVI.

TELEPHONE.

336. The telephone may be defined to be an instrument for transmitting musical sounds and articulate speech from one point to another.

In all telephonic arrangements worked by electricity, we

have essentially three things—a *transmitter*, a *receiver*, and a closed circuit which includes both transmitter and receiver, and which may or may not also include some form of battery. The function of the transmitter is to produce variations of the current-strength in the circuit when under the influence of sonorous vibrations; and the function of the receiver is to translate these variations into sound, and so reproduce, at the distant station, the sounds which were uttered into the transmitter.

According to Ohm's law, if C be the current-strength, E the electro-motive force, and R the resistance in any electrical circuit, we have $C = \frac{E}{R}$, and, hence, we see that the current strength in any circuit can be varied in two distinct ways, either, first, by varying the resistance and keeping the electro-motive force constant, or, secondly, by varying the electro-motive force and keeping the resistance constant. These two ways of varying the current-strength give rise to two distinct classes of telephone, of which we shall now give examples, although it will be impossible for us even to allude to many of the forms of telephone which have either been proposed or are in actual use.

337. *Reiss's Telephone.*—This is an example of a telephone which is worked by varying the resistance in the circuit, the electro-motive force being constant. It was invented by Philip Reiss in 1861, and is represented in fig. 215. AA is a hollow wooden box, with two round holes in it, one on the top, the other in front. The hole at the top is closed by a piece of bladder, S, tightly stretched on a circular frame; a mouth-piece, M, is attached to the front opening. When a person sings in at the mouth-piece, the whole force of his voice is concentrated on the tight membrane, which in consequence vibrates with the voice. A thin strip of platinum is glued to the membrane, and connected with the binding screw *a*, in which a wire from the battery, B, is fixed. A tripod, *efg*, rests on the skin. The feet *e* and *f* lie in metal cups on the circular frame over which the skin is stretched. One of them, *f*, rests in a cup containing mercury, and is connected with the binding screw

b. The third foot, *g*, consisting of a platinum point, lies on the circular end of the strip of platinum just mentioned. This point being placed on the centre of the oscillating membrane, acts like a hopper, and hops up and down with it. It is easy to understand how, for every vibration of

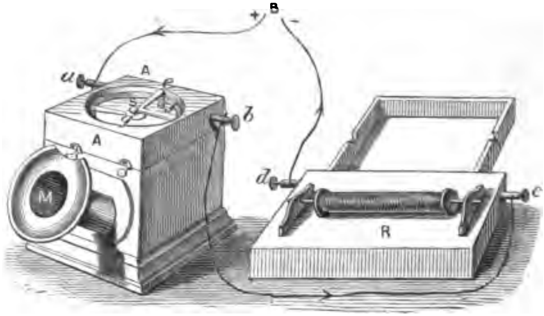


Fig. 215.

the membrane, the hopper will be thrown up for the instant from connection with its support, and how the close circuit is thus broken at every vibration. The receiving apparatus, R, consists of a coil of wire placed in circuit, inclosing an iron wire, both being fixed on a sounding-box. The connections of the various parts of the circuit are easily learned from the figure. Suppose a person to sing a note at the mouth-piece which produces 300 vibrations a second, the circuit is broken at the bladder 300 times, and the iron wire ticking at this rate gives out a note of the same pitch. The note is weak, and in quality resembles the sound of a toy trumpet. Dr Wright devised a receiving apparatus of the following kind. The line current is made to pass through the primary coil of a small induction coil. In the secondary circuit he places two sheets of paper, silvered on one side, back to back, so as to act as a condenser. Each current that comes from the sending apparatus produces a current in the secondary circuit, which charges and discharges the condenser, each discharge being accompanied by a sound like the sharp tap of a small hammer. The musical notes are rendered

by these electric discharges, and are loud enough to be heard in a large hall.

338. *Bell Telephone.*—The Bell Telephone, so called from its inventor, Professor Graham Bell, is an example of a telephone which is worked by varying the electro-motive force and keeping the resistance constant. In this form the transmitter and receiver are identical; and no battery is included in the circuit, the working current being an induced current due to the variation of the magnetic intensity within a helix of wire. Fig. 216 shews a sectional sketch of two Bell telephones arranged in circuit so as to transmit articulate speech.

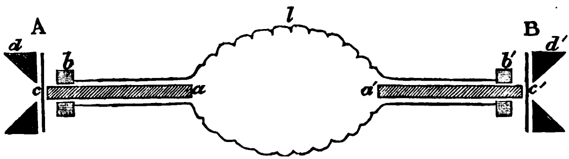


Fig. 216.

Let A denote the transmitter and B the receiver, *l* being the connecting line wire; *a* and *a′* are two cylindrical steel magnets, each about six inches long, and a quarter of an inch in diameter; *b* and *b′* are two small wooden bobbins surrounding the north poles of the magnets, and filled with a good many turns of fine insulated copper wire, the ends of wire being put into connection with the line wires; *c* and *c′* are two thin circular discs of iron (usually ferrotype plate) fixed close to, but not touching, the poles of the magnets; *d* and *d′* are two conical wooden pieces for applying the mouth to in the one case, and the ear in the other.

Suppose now that a person speaks into the transmitter at A. The sound-waves striking against the disc *c*, set it into vibration, and hence *c* may be regarded as an armature moving rapidly in front of the pole of the magnet *a*. These vibratory motions produce corresponding variations in the magnetism of *a*, and these again cause corresponding induced currents in the wire of bobbin *b*. These induced currents flow along the line wires to the receiver, B, and passing

through the bobbin b', produce corresponding changes in the magnet a'. These changes of magnetism affect the iron disc c', and put it into vibrations which are sympathetic with those of c. Hence c' gives out sounds precisely corresponding to, but less loud, than those directed against c, and hence an ear applied at d' hears the words uttered by the mouth at d. The speech produced by the Bell telephone, although not very loud, is exceedingly distinct; so much so, that one has no difficulty in recognising the voice of the speaker. But perhaps the greatest marvel of this ingenious instrument is its extreme delicacy in detecting variations in even the most feeble current, provided these variations are rapid enough. Professor Tait has calculated that the current from a single Grove's cell, acting through a resistance of a billion B.A. units, is sufficient to work a telephone, provided the current is varied five hundred times per second. Hence the telephone is by far the most delicate instrument yet invented for detecting minute and sudden variations in the strength of a current.

Fig. 217.

The Bell telephone in its usual complete form is represented in fig. 217.

339. *Microphone.*—The microphone, invented by Professor Hughes, is an instrument which produces rapid variations in the resistance of an electrical circuit when acted upon by any kind of vibratory or tremulous motion. It consists essentially of two or more conductors in loose contact, such as is produced by letting the conductors rest lightly the one against the other. When the loose contact is placed in circuit with a cell and a Bell telephone, any tremor acting upon the loose contact varies the resistance at the surfaces in

contact, and is announced by a loud sound in the telephone. It is for this reason that it is called the microphone, inasmuch as it makes audible, in the telephone, such faint tremors as those produced by the ticking of a watch, or even the tread of a fly across a wooden board. Almost any two conductors in loose contact, whether of the same or different materials, will produce the microphone effect; but it has been found that the best effect is produced by a loose contact between two pieces of gas-carbon. No doubt, the peculiar excellence of carbon in this respect is due to its more or less gritty nature, and also to the fact that it does not readily oxidise by exposure to the atmosphere. The usual form of microphone, when arranged so as to be acted upon by faint tremors, is represented in fig. 218. A and B are two small blocks of carbon attached to a vertical piece of wood which is supported on a horizontal sole-plate, also of wood. C is a small stick of carbon, pivoted at both ends, and supported vertically in conical holes between the two carbon blocks. The carbon stick is thus in a position of extreme instability, and any tremor communicated to the wooden supports will cause it to oscillate. The current from a small battery is led through the carbons and a Bell telephone, and the arrangement is complete. When a watch is placed on the sole-plate of the instrument, every tick is distinctly heard in the telephone; and when a fly is allowed to creep over any part of the instrument, every tread is also revealed in the telephone. Further, if a person sing or speak in the neighbourhood of the instrument, the sonorous vibrations are communicated to the support of the carbon blocks,

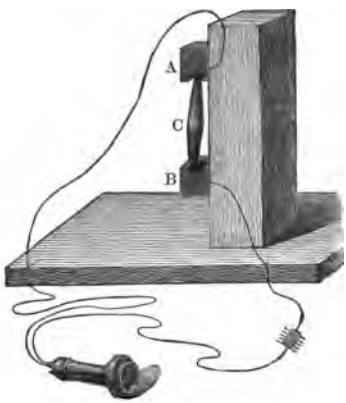


Fig. 218.

and thence to the carbon stick, which is thus thrown into a corresponding state of vibratory motion. The resistance of the circuit is in this way varied, and every sound is faithfully reproduced in the telephone.

A difference of opinion prevails among physicists regarding the real cause of the microphone action. Some, and these of the highest authority, hold that the action is due merely to the variations of resistance due to variations of pressure at the surfaces of contact of the carbons. It is difficult, however, to see how this can be the whole, or even the main cause of the action; for we must remember that the surfaces of the carbon in contact are continually changing in virtue of the minute electric arcs which must take place between the points of carbon which are just clear, and no more, of contact. And if the surfaces in contact are thus perpetually changing, it is hardly possible that the pressure between them could vary according to any law sufficiently regular to account for the transmission of articulate speech. It seems highly probable that the microphone is more of the nature of a very refined make-and-break, and thus analogous to the Reiss transmitter, but only immensely more delicate. As a matter of fact, we know that when the microphone is used to transmit musical sounds of a definite pitch, it does act as a make-and-break, for sparks can be seen between the carbon points; and there does not seem to be any good reason for supposing that this make-and-break action entirely ceases, and a perfectly different action comes into play, when the instrument is used to transmit articulate speech.

340. *Microphone Transmitters.*—The chief practical application of the microphone is its employment as a transmitter to a Bell telephone as receiver. For this purpose it has been found very effective, and is now almost universally adopted. The forms of microphone transmitter are very various, all depending upon the same principle, and differing only in matters of detail. A common form is represented in fig. 219, which shews the arrangement of telephone and transmitter at one end of the line as used for carrying on a conversation. The sloping lid of the box is made of a thin

deal board, to the under side of which the microphone is attached. In this form the microphone usually consists of several sticks of carbon radiating from a central carbon block, and supported, at the outside, by a suitable number of other blocks placed equally distant round the central block. The

Fig. 219.

sticks rest loosely in pivot holes in both of their supporting blocks. The current is led from the central block through each of the carbon sticks and away to the line wire. The speaker simply holds his head over the sloping lid at a convenient distance, and speaks not loudly but distinctly. Excessive loudness is a mistake, as it produces roaring in the telephone.

341. *Telephone Exchange.*—In most large towns a system of telephone exchanges has recently sprung up. The object of these exchanges is to enable business and professional men to converse directly with each other at any moment. For this purpose a convenient central station is chosen from which wires are led to the houses or business places of all the individuals who subscribe to the exchange. At the central station a staff of attendants, usually girls, are always present, and a system of switches is arranged whereby an

attendant can, at a moment's notice, place any one member of the exchange in direct communication with any other. This is accomplished by merely inserting a plug which completes the electrical circuit between the one and the other. Suppose A wishes to communicate with B. A first rings up the attendant, and tells him to join him on to B, all the members being known to the attendant and to each other by each having a separate number. The attendant then inserts the requisite plug, and A and B are ready to converse directly with each other, without the attendant or any one else knowing what is said. When the conversation is ended, a signal is sent to the attendant, and the plug is withdrawn.

342. *The Microphone as a Receiver.*—The curious fact has been discovered that the microphone can act as a receiver as well as transmitter, although imperfectly. This can be readily shewn by the following experiment due to Professor Blyth. Two ordinary porcelain jam-pots, of convenient size, are taken, and half filled with cinders or gas carbon in small lumps. Down the sides of each pot two strips of copper are inserted, facing each other, to serve as electrodes. The two jam-pots are then placed in circuit with a battery of four or five Grove's cells. If a song be sung into one of the jam-pots, a listener can hear it quite distinctly proceeding from the other, on applying it to his ear. Articulate speech can also be transmitted in this way so as to be quite recognisable, although it comes out rather squeaky.

343. *Edison's Telephones.*—Mr Edison of New York has invented a variety of ingenious forms of telephone, the most interesting of which, perhaps, are his *carbon button transmitter* and his *slipping receiver.* The carbon button consists of a small thin cylinder made from compressed paraffin smoke mixed with gum water. This button is placed between two pieces of platinum foil, which serve as electrodes for sending a current through it. The button with the foil is placed between a rigid support at the one end and a flexible ferrotype disc at the other. Usually, a small pad of india-rubber is inserted between the button

and the flexible disc. When sonorous vibrations are sent against the disc, its to-and-fro vibrations cause more or less compression throughout the mass of the carbon button, and so vary its resistance. In this way, when in circuit with a battery, it is made to act as a transmitter to any suitable form of receiver.

The action of the slipping receiver depends upon the fact, discovered by Mr Edison, that the friction between a metallic spring and a revolving cylinder of prepared chalk soaked in an electrolytic liquid, varies when a current passes between the surfaces in contact. When the current passes, the friction is diminished, as if the chalk were oiled; and when the current ceases, or is weakened, the friction is increased. In the actual instrument the small chalk cylinder is driven slowly round by hand. One end of a steel spring presses against the surface of the chalk, the pressure being regulated by a pad of india-rubber. The other end of the spring is attached to the centre of a mica disc. Now, when the current through the spring and chalk cylinder is made to vary by the action of the transmitter, the friction is alternately increased and diminished; and this gives a series of rhythmical jerks to the mica disc, which make it speak out loudly and distinctly the words uttered into the transmitter. This instrument, notwithstanding its ingenuity and scientific interest, is apt to get out of order, and has not come as yet into very general use.

344. *Photophone.*—This is the name given to a form of telephone transmitter which is acted upon by light instead of sound. It was introduced by Professor Graham Bell. Its action depends upon the fact, first discovered by Willoughby Smith, that crystalline selenium has its electrical resistance altered on exposure to light. To construct a photophone, or, as it is sometimes called, a selenium cell, we may proceed as follows: Procure two small brass combs with fine long teeth. From each knock out every alternate tooth, and then place the two combs on a flat mahogany board, with the teeth interlacing but not touching at any point. In this position screw them firmly to the board, and solder a wire to each comb to serve as electrodes. Next procure a stick of good selenium,

and having warmed the combs sufficiently to melt the selenium, rub it in carefully between the teeth. In this condition the selenium is in the amorphous state, and must be rendered crystalline by heating the whole cell in an air-bath to about 240° C., and then allowing it gradually to cool. If the cell be now included in circuit with a galvanometer and a battery of 15 Grove's cells, its resistance will be found to alter when exposed to light.

When the cell is put in circuit with the battery and telephone, and an intermittent light thrown upon it, corresponding sounds are heard in the telephone. This can be prettily illustrated by placing the flame of a Koenig's capsule, provided with a mouthpiece, in front of the cell, and singing or speaking into the mouthpiece. The alterations in the flame so affect the resistance of the selenium as to make the singing and speaking quite recognisable in the distant telephone. If a singing flame be put in front of the cell, the music of the flame is beautifully reproduced in the telephone.

Electrical Storage of Energy.

345. The simplest example of the storage of energy by means of electricity is perhaps a charged Leyden jar. In this we have energy stored in the potential form of electrical separation; the inside coating having usually a positive charge, and the outside coating the corresponding negative charge. When the knob and outside are joined by the discharging tongs, we have the stored energy recovered in the form of the sound, heat, and light of the spark. Another simple example of the same thing is the counter electro-motive force of polarisation always set up in an ordinary voltameter when a current is sent through it. When the current flows, it carries hydrogen with it, and sends oxygen in the opposite direction. In this way, a layer of oxygen is formed on the one platinum plate, and a layer of hydrogen on the other. When the battery is removed from the circuit, and the platinum plates are joined by a wire, a momentary current passes through the wire in the opposite direction to that of the charging current. This can easily be tested by a galvanometer.

346. *Planté's Secondary Battery.*—A Planté's cell is in

reality a huge voltameter, in which the platinum plates are replaced by plates of lead. In order to get a large surface in a convenient space, it is usually constructed as follows: Two large sheets of lead are placed the one on the top of the other, with narrow strips of india-rubber between them. The two sheets are then rolled up together, so that the one forms a spiral coil insulated within the other. The whole is then placed in a deep glass jar with acidulated water. Wires are soldered to each plate to serve as electrodes. When the current from two or three Bunsen's or Grove's cells is sent through the secondary cell for a considerable time, layers of oxygen and hydrogen are gradually formed on the respective lead plates, and this process goes on till the electro-motive force of polarisation is equal to that of the charging battery. In this state the action ceases, and we have the energy of the battery stored in the cell. When the battery is now removed, and the electrodes of the cell are joined by a wire, a powerful current passes through the wire for a short time. The duration of the discharging current depends upon the resistance of the wire through which it has to pass. Thus, a cell which will keep a thick wire red-hot for only a few minutes, will keep a fine platinum wire in a state of incandescence for nearly an hour.

Planté has found that the action of his cell is greatly improved by the process of what he calls 'forming' the plates. This is performed by charging the cell alternately in opposite directions for stated times, and discharging it between each reversal of the charging battery current.

In order to get great effects, Planté has constructed secondary batteries consisting of a great number of cells; and he has also adopted an ingenious device for charging a number of cells side by side, and then discharging them in series. In this way he gets an enormous electro-motive force, sufficient to produce sparks in air resembling those of an induction coil.

347. *Faure Cell.*—This cell, invented by M. Faure in 1880, is the most recent improvement in secondary batteries. It is constructed as follows: Two thin lead plates of convenient length and width are taken. Each of these is first coated

with a layer of red lead about ⅛ inch thick. The red lead is made into a thick paste with dilute sulphuric acid, and spread evenly over the surface of each plate. The plates thus coated are next covered with a layer of felt or flannel, or, what answers very well, three or four folds of filter paper. The two plates may then be either rolled together, as in the Planté cell, or folded backwards and forwards so as to be put into a rectangular box lined with lead. The liquid used is dilute sulphuric acid, in which the plates are immersed. The great advantage of this cell over the Planté is, that it takes very short time to 'form,' and the discharging current does not run down so quickly. When a battery of a number of Faure cells is charged with a dynamo-machine, it will give out a current sufficient to work a number of incandescent lamps for a whole evening, and in this way it is employed for household electric lighting. The Faure battery has also been successfully employed in lighting up the carriages in underground railways, the charging current being got from a dynamo-machine driven by the train when in motion.

The chemistry of the Faure cell can hardly as yet be said to be fully understood; but there seems no doubt that when the charging current passes, spongy lead is formed on the one plate, and peroxide of lead at the other.

CHAPTER XXVII.

ELECTRO-OPTICS, OR THE CONNECTION BETWEEN LIGHT AND ELECTRICITY AND MAGNETISM.

348. According to the undulatory theory of light, now universally adopted, light is supposed to consist of undulations propagated from the luminous source through a very subtle elastic medium called the *luminiferous ether*. The vibrations of the ether particles, which produce these undulations, are also supposed to take place in all directions in planes perpendicular to the direction in which the ray of light is going. This latter assumption is rendered necessary in order to explain

the observed facts of the polarisation of light, for an account of which we must refer the student to some work on Physical Optics.

349. *Electro-magnetic Theory of Light.*—According to this theory, for which we are indebted to Clerk Maxwell, both light and electro-magnetic induction are supposed to be influences propagated through the same medium—the luminiferous ether—and in fact light itself is supposed to be only a particular form of electro-magnetic disturbance. If the theory be true, we ought to expect to find some relations subsisting between the phenomena of the propagation of light through any medium, and the phenomena of the propagation of electro-magnetic induction through the same medium. Several such relations have been pointed out by Clerk Maxwell, which tend to confirm the theory.

If V be the velocity of electro-magnetic induction in any medium, K its specific inductive capacity in electro-static units, and m its coefficient of magnetic induction, then Clerk Maxwell has shewn by a mathematical analysis that we have the equation

$$V = \frac{1}{\sqrt{Km}} \qquad (1)$$

If we take air as the medium, and use electro-magnetic units, we have $m = 1$, and $K = \frac{1}{v^2}$, where v is the number of electro-static units in one electro-magnetic unit. Substituting in (1), we have $V = v$. Now, the value of v has been found by several independent experiments, the mean of which gives

$$v = 2{\cdot}9857 \times 10^{10} \text{ centimetres per second,}$$

or

$$v = 185{,}521 \text{ miles per second.}$$

The velocity of light has also been found by various independent methods, the most satisfactory of which are the determinations by Cornu in 1874, and by Young and Forbes in 1881. Calling the velocity of light in air L, we get from these experiments $L = 2{\cdot}9857 \times 10^{10}$ centimetres per second.

Comparing the values of L and V, we see that the velocities

of light and electro-magnetic induction in air are exactly identical.

Assuming the same to be true for any other transparent non-conducting medium, we can find a relation between the index of refraction of the medium and its specific inductive capacity. Let μ be the index of refraction from air into the medium, K its specific inductive capacity, and m its co-efficient of magnetic induction. Then if V_1 denote the common velocity of light and electro-magnetic induction in the medium, we have from the principles of optics,

$$V_1 = \frac{L}{\mu}.$$

Also from (1), since m is nearly unity for all transparent media, we have

$$V_1 = \frac{v}{\sqrt{K}}$$

in electro-magnetic measure.

Hence we have $$\frac{L}{\mu} = \frac{v}{\sqrt{K}}.$$

But we have already seen that $L = v$, and therefore $\mu = \sqrt{K}$; that is to say, if the electro-magnetic theory of light be true, the index of refraction of a medium should be equal to the square root of its specific inductive capacity. We have thus a test of the theory by comparing a table of refractive indices with a table of specific inductive capacities, it being remembered, however, that we must take the refractive index for waves of infinite wave length. The following table shews the comparison according to Gordon:

Dielectric.	$\sqrt{K}$.	μ ($\lambda = \infty$).
Double flint-glass, extra dense..	1·778	1·672
Extra dense flint-glass..........	1·747	1·620
Hard crown-glass	1·763	1·504
Paraffin.........................	1·412	1·422

350. *Action of Magnetism on Light.*—The first clear connection between magnetism and light was pointed out by

Faraday in 1845. He experimented first with a particular kind of glass called 'heavy glass,' which is a silicated borate of lead, but he afterwards found that many other substances could produce the same effect. His experimental arrangements were as follows: A piece of heavy glass, about two inches square and half an inch thick, was placed lengthwise between the poles of a powerful electro-magnet, in such a position that a pencil of light could be sent through it in a direction as nearly as possible parallel to the line of magnetic force. The light from an Argand lamp was polarised in a horizontal plane by reflection from a piece of glass placed at the proper polarising angle. The polarised beam was passed through the heavy glass, and after emergence, was led through a Nicol's prism, so placed that it could rotate round an axis parallel to the direction of the ray. This Nicol acted as the analyser. Before the current was sent through the electro-magnet coils, the analysing Nicol was placed at the proper angle for extinguishing the light of the lamp. When the current was now turned on, the light instantly reappeared, and continued to come through so long as the current flowed, but immediately disappeared when the current was turned off. When the current was on, and the light coming through the Nicol, Faraday found that the Nicol had to be rotated through a definite angle in a definite direction before the light was again extinguished; and that the direction of rotation was reversed when the poles of the magnet were reversed by reversing the current. He also found that the amount of rotation required to produce extinction of the light was proportional to the strength of the magnetic field, and to the length of glass through which the light had to pass.

This shewed that the magnetic action had the power of rotating the plane of polarisation, and that the angle of rotation varied continuously from point to point through the glass, and that the amount of rotation was proportional to the difference of magnetic potential between the point where the light entered, and the point where it left the glass.

The direction of rotation is related to the direction of the lines of force, in the same way as the rotation and longitudinal motion of an ordinary cork-screw.

Since Faraday's time this subject has been carefully examined by Verdet, Becquerel, Röntgen, and others, who have found the effect to be produced not only by solid, but also by liquid and gaseous dielectrics. They have also tabulated the magnetic rotative powers of the various substances for light of different colours.

Another remarkable action of magnetism upon polarised light has recently been discovered by Dr Kerr of Glasgow. He reflects a beam of polarised light from the highly polished pole of a powerful electro-magnet. In the path of the reflected light, a Nicol's prism is placed in such a position as to produce extinction of the light when no current goes through the magnet. Directly the current is turned on, the light reappears, and continues so long as the current flows, shewing that the plane of polarisation has been rotated by the magnetic action.

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THE END.

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